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Deliverable Abstract

This report presents the GROOM RI design of a software ecosystem to allow the upscale of MAS operations facilitating the uptake of fit to purpose collaborative software tools and the integration of modern automation and AI systems.

Deliverable executive summary

Multiple organisations across Europe have been successfully operating MAS for years, but the current approach has severe scalability problems and does not allow cooperative operation with adapted access controls; sharing resources is limited by technology as it is the development of automation.

Organisations using gliders and other MAS have to operate them manually or develop their own automation systems, which increases development and maintenance costs. AUV manufacturers need more incentives to develop systems that could interface easily with other piloting systems or AUVs from different vendors, limiting MAS's interoperability.

More complex scientific MAS missions involving larger fleets are prohibitable or non-repeatable. Planning and labour requirements, alongside other operational costs, grow dramatically with the increase in the number of assets deployed.

The main goal of the presented design is to facilitate the adoption of piloting tools that meet the challenge of a multi-platform approach to any number of MAS, do collaborative mission planning, help distribute piloting and increase the uptake of AI systems. The ecosystem must also help reduce the need for dedicated IT for smaller groups and ease the system integration tasks.

The role of the future GROOM RI in creating an ecosystem that centralises and coordinates resources, identifies common problems and avoids duplication is critical here due to several reasons. Firstly, many organisations dedicated to ocean observing suffer from a shortage of human resources to develop operational IT infrastructure that meets current software engineering and IT services standards. Secondly, there is a lack of standards and interoperability of MAS ecosystems, which requires championing such activities. Finally, there is a shortage of open-source tools for command and control of MAS from most manufacturers or institutions.

This design study provides a vision and a disruptive and innovative design of what this autonomous ecosystem can be. The design has produced the following recommendations:

Recommendation [1]: GROOM RI must create a Cyber Infrastructure and Command and Control Working group.

Recommendation [2]: GROOM RI must find sustained funding to deliver a community-driven command and control ecosystem.

Recommendation [3]: GROOM RI must design an open autonomy ecosystem to allow scaling up autonomy.

Recommendation [4]: GROOM RI must push international standards to enable the interoperability and integration of MAS C2 systems, collaborating with important players in this field such as CMRE.

Recommendation [5]: GROOM RI must develop all the autonomy ecosystems as individual containerized solutions that can be used standalone.

Recommendation [6]: GROOM RI must develop the autonomy ecosystem in a way it is easy to deploy and use by non-DevOps users; for example, a non-expert user should be able to deploy the systems as services in the EOSC with a couple of clicks.

Recommendation [7]: GROOM RI to become an EOSC provider of digital services.

Recommendation [8]: GROOM RI should amalgamate the existing expertise and know-how from the LSTS Toolchain and NOC C2 ecosystem and use them as the base of the new GROOM RI infrastructure with its RI user-oriented philosophy.

Recommendation [9]: GROOM RI must demonstrate the added value to communities with demonstrators of coordinated multi-institution deployments of MAS operated using the GROOM community tools.

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AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
ASW	Anti-Submarine Warfare
AOSN	Autonomous Ocean Sampling Network
AUV	Autonomous Underwater Vehicle
C2	Command and Control
CANON	Controlled, Agile, and Novel Observing Network
CATL	Collaborative Autonomy Task Layer
COOP	Cooperative Ocean Observatory Portal
EGO	European Glider Observatories, became Everyone's Glider Observatories
EOOS	European Ocean Observing System
EOSC	European Open Science Cloud
GCOS	Global Climate Observing System
GDAC	Global Data Assembly Centre
GOOS	Global Ocean Observing System
HOPS	Harvard Ocean Prediction System
MCM	Mine Counter Measurements
MAS	Marine Autonomous Systems
MASSMO	Marine Autonomous Systems in Support of Marine Observations
MOQuA	Metadata Oriented Query Assistant
NMEP	National Marine Equipment Pool
NOC	National Oceanography Centre
OOSs	Ocean Observing Systems
PI	Principal Investigators
ROMS	Regional Ocean Modelling System
SSDS	Shore Side Data System

Table 1 - List of abbreviations

1. Background and motivation

The use of marine autonomous systems (MAS) for ocean observation is rapidly increasing, with more and more research institutions adopting gliders and other MAS to improve their understanding of the ocean. A decade ago, just a handful of organisations operated gliders, and nowadays, most European countries have at least one glider operator, and this is also the case in a growing number of countries in the South or who collaborate with European countries. There are multiple operators in all the large countries (France, Germany, Italy, Spain and UK), and an important growth in the northern European countries (Norway and Sweden). A decade ago, aggregated numbers of days in the water a year were counted in hundreds, while today, there are thousands. This does not even take into consideration other AUV platforms, with again more and more operational AUVs outside of the French, German and UK national pools, such as academic institutions like the University of Porto LSTS or University of Girona CIRS which produce bleeding edge technology that has now been successfully moved into commercial ventures. Talking about the trading sector, we can now see successful commercial companies providing glider services like the GROOM II partner CSCS or Blue Ocean Monitoring. The uncrewed surface vehicle landscape witnessed a massive explosion of developers and operators, and the number of assets in the water nowadays is nowhere near where underwater gliders were ten years ago, at the time of the FP7 GROOM project.

While MAS's hardware manufacturing and operating reliability have dramatically improved, mission planning and piloting MAS remains a highly manual activity based on manufacturers' software with limited functionality for the needs of research performing organisation operators and even the above-mentioned companies.

To improve the situation, the GROOM II project has agreed on the following mission statement for the future GROOM RI:

This European Research Infrastructure integrates national infrastructures for Marine Autonomous Systems (MAS) to provide access to platforms and services to the broadest range of scientific and industrial users and other ocean observing RIs. ***It maintains a unique centralised provision of cyber-infrastructure, data, and knowledge for the optimised use of MAS*** *to study climate and marine environments and to support operational services and the blue economy.*

To optimise the use of gliders and other MAS and provide added value to operations and advancements to the current state of the art, the future GROOM RI will need to facilitate the utilisation of adequate piloting systems (henceforth, Command and Control system or C2) for widespread adoption by users of the infrastructure. This requirement for the GROOM RI ensures that the scale and complexity of future MAS deployments are embraced and feasibly supported by the nodes of the future infrastructure.

In this document, we propose a cyber-infrastructure architecture design to make future operations scalable, adaptable, upgradable to artificial intelligence (AI) and repeatable, benefiting future GROOM RI partners and stakeholders, as well as the wider scientific communities. We also provide an overview of the state of the art of MAS piloting and planning tools (with a particular focus on gliders), reviewing past missions accomplished by various organisations or research institutes in the domain of assembling fleets of MAS and deployment of AI systems to support those missions.

2. Document structure

This document is the result of 3 years of joint work leveraging years of experience operating and developing MAS and C2 systems and addressing the requirements and use cases expressed by the other work packages. The document has been structured to allow reviewers to quickly get to the point and read the design, but to reach this design a considerable amount of time has been spent reviewing the history and state of the art of C2 systems for ocean observing. All this information has been included in appendixes to allow anyone reading this document to understand the state of the field of C2 systems at the moment of writing this report. The reader must consider this very carefully as C2 systems are evolving rapidly, so some of the features and systems we have reviewed may look completely different in the future.

Recommendations expressed under each section have been collated in Conclusions.

3. The GROOM Autonomy Ecosystem

Institutions using gliders and other MAS require software tools to operate the physical assets deployed at sea. Traditionally, to do over-the-horizon operations, the vehicles use a satellite link to call back to a machine that is accessed by operators. The vehicle manufacturers provide that machine. A thorough review of the different tools provided by glider manufacturers is developed under Appendix 1. Still, here we want to explain the general operational principles and struggles experienced by different organisations.

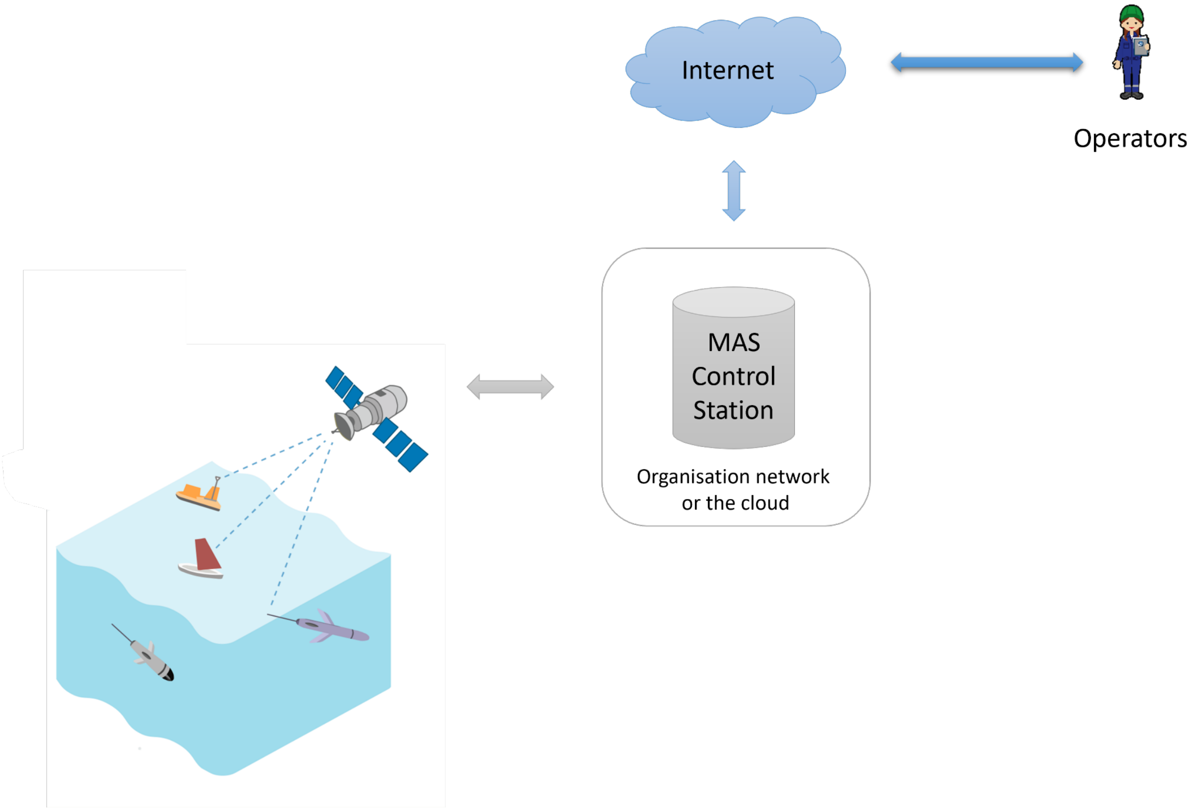

Figure 1 – Communication flow between operators and MAS, including relevant systems like the control stations

Figure 1 shows the current general architecture and flow to operate gliders and other MAS; on the left, the deployed MAS communicates back using satellite communications, and those communications get routed to the MAS control stations. Operators connect to those control stations remotely to change the MAS configuration and check the data. The stations can run on the organisation's premises, or be offered as a service by the vehicle manufacturers or specialised companies. Organisations need to devote resources to maintaining the control stations, installing the original software, patching the operating system and backing up the data. Some organisations have IT services to deal with this, others don't, but in general, it hinders research groups from doing these tasks on top of maintaining and operating gliders. Things become more problematic when wanting to share the piloting with external organisations as part of collaborations, as this will need requesting to open firewalls or create users. All these tasks require proper management so they don't create cybersecurity issues in the future.

Research institutions and organisations using gliders and other MAS find themselves having to operate these assets largely manually or having to develop their own in-house automation system to assist continuous piloting over the horizon, which adds to the costs of development, maintenance, and operation of MAS. Furthermore, historically, AUV manufacturers would need more incentives to develop systems that could interface easily with other piloting systems or AUVs from different vendors, thus allowing MAS's interoperability. And the small number of manufacturers and the competition have obviously not allowed these incentives to have an effect.

More complex scientific MAS missions involving larger fleets are prohibitable or non-repeatable. Planning and labour requirements, alongside other operational costs, grow dramatically with the increase in the number of assets deployed.

With most research or even dedicated operational groups having a limited number of people available but still having the requirements of increasing the number of ocean observations performed by MAS, there is the need to automate parts of MAS operation, enabling operators to control and supervise fleets of MAS instead of single platforms. Moreover, MAS can be operated in complex configurations with assets belonging to different nodes, providing services for multiple users during the same mission. Therefore, the Command and Control (C2) systems must be suitable for controlling and automating several heterogeneous systems and enable multiple users' distributed coordinated and simultaneous intervention.

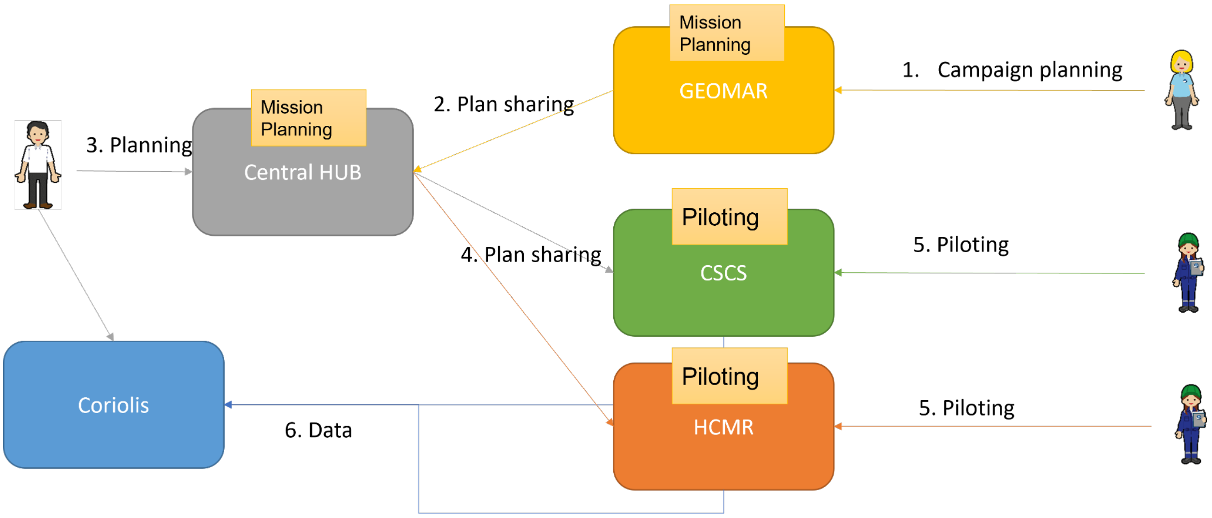

Figure 2 – Example of a distributed workflow

Figure 2 shows an example of a distributed workflow: a Geomar scientist wants to perform an operation but does not have enough MAS units available, and the GROOM RI can fill the capability. The scientist creates the plan and shares it with the central hub, which helps in doing the planning. The plan is then shared with two GROOM RI nodes (in this imaginary example, CSCS and HCMR) that perform the piloting collaboratively while the data is sent to the DAC.

This is an example workflow of an imaginary operation ; nowadays, that kind of distributed operation requires the different partners to exchange plans using emails, attaching the plans to heterogeneous formats like Word documents, KML files or any other format. There is no single point to follow the piloting or exchange and track operational decisions.

While the need for C2 systems is particularly critical for MAS operation, other platforms may need such an approach. Indeed, fixed point observatories (moorings) are remotely operated systems that use over-the-horizon communications or cabled transmission. Autonomous systems are also installed on Research Vessels or commercial ships with no human intervention from the crew. Our architecture has been designed to be scalable and distributed making it appropriate for such operations of a series of very different platforms.

In this section, we focus on designing a digital ecosystem to facilitate the adoption of advanced autonomy to help with MAS operations. The future GROOM RI is the proper structure to occupy the intersection between ocean-observing communities, robotics, and AI research. The future GROOM RI will develop the underlying cyber-infrastructure and push the MAS-C2 interoperability needed to allow those communities to work together.

Before going into the details of our design, we need to explain why individual organisations can't develop this independently. Hence, the role of GROOM RI is critical to push this:

- **Lack of human resources to develop operational infrastructure**. Most teams can't afford dedicated software developers, having to give priority to technicians and engineers to keep the MAS operational, such as integrating and calibrating sensors while also operating gliders and other MAS. Developing and maintaining piloting systems requires dedicated software engineering teams;

- **Lack of standards and interoperability of MAS ecosystems**. Manufacturers have yet to produce machine-to-machine standards, allowing operators to easily integrate commercial MAS platforms into the broader command and control ecosystems. This exacerbates the problems of point number one, requiring more experienced software engineers to integrate every manufacturer's proprietary MAS piloting system;

- **Lack of resources to maintain, run, patch, and update IT systems.** Teams already need help to keep their MAS control stations running. In the best cases, teams can leverage their organisational IT groups to help them run the systems needed to operate gliders and other MAS. In the worst case, engineering team members have to maintain the machines to operate the MAS, increasing their workload and preventing them from doing other scientific or operational tasks;

- **Lack of open source tools for command and control of MAS from most manufacturers or institutions[1].** Proprietary MAS software from manufacturers, automation development works by research institutions, and C2 interfaces such as NOC C2 (though there are plans to open-source it) are mostly not open-sourced. C2 systems like the one developed by LSTS, Neptus, whilst open source, require significant expertise to run and operate;

The reality is that planning and operating gliders and other MAS require multiple sets of tools independently developed or utilised by various groups while providing access to the whole with rules meeting several criteria. This further adds to the maintenance and training resources required for starting new operators.

The major obstacle to broader uptake of developing more autonomy and capabilities for conducting more ambitious scientific missions is due to the smaller size groups running MAS or the nature of the institutions in which the groups are based, focusing primarily on ocean sciences research, where it is challenging to justify or fund a dedicated software group to develop their technical capabilities further.

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[1] A review of C2 tools is available in Appendix 1.

GROOM RI will add value by advocating collaborations, aggregating efforts across the infrastructure and community, and acquiring funds to support, promote, and undertake such activities directly.

Presently, there is no organisation coordinating initiatives around MAS interoperability or the associated C2 infrastructure. Working groups under the Global Ocean Observing System (GOOS) program, such as the OceanGliders or the EuroGOOS glider task team, operate around coordinating operations, improving data workflows, recommending data infrastructure development, and developing best practices. The development of piloting and automation services remain niche activities for groups in bigger institutions in the network (such as NOC or CNRS in Europe, and WHOI, Scripps, and MBARI in the US, among others) and academic researchers, particularly in the robotics field (such as the University of Porto, University of Girona and others), but still without any prospect of interoperability between these groups. However, in many cases, these institutions do not operate in the ocean observing (monitoring) space nor for the needs of the maritime sector, as the GROOM RI will. This gap needs to be closed to foster growth, development, and coordination efforts for advancing ocean science research and ocean observing across Europe.

The GROOM RI will facilitate more collaborations among scientists in the academia and operational groups, coordinating funding and proposals and taking a strategic view of the need for development to improve the landscape. The future GROOM RI must assemble a focused group dedicated to these activities with experts in autonomy and operational MAS alongside other stakeholders. The group must strategically manage GROOM's piloting cyber infrastructure evolution, co-designing it with other EU marine RIs and considering the emerging GOOS needs.

Recommendation [1]: GROOM RI must create a Cyber Infrastructure and Command and Control Working group.

Recommendation [2]: GROOM RI must acquire funding to deliver a community-driven command and control ecosystem.

3.1 - GROOM Autonomy Ecosystem Design

The main goal of our design is to facilitate the adoption of better piloting tools, do collaborative mission planning, help distribute piloting and increase the uptake of AI systems. The ecosystem must also help reduce the need for dedicated IT for smaller groups and ease the system integration tasks. The following figure shows the proposed architecture.

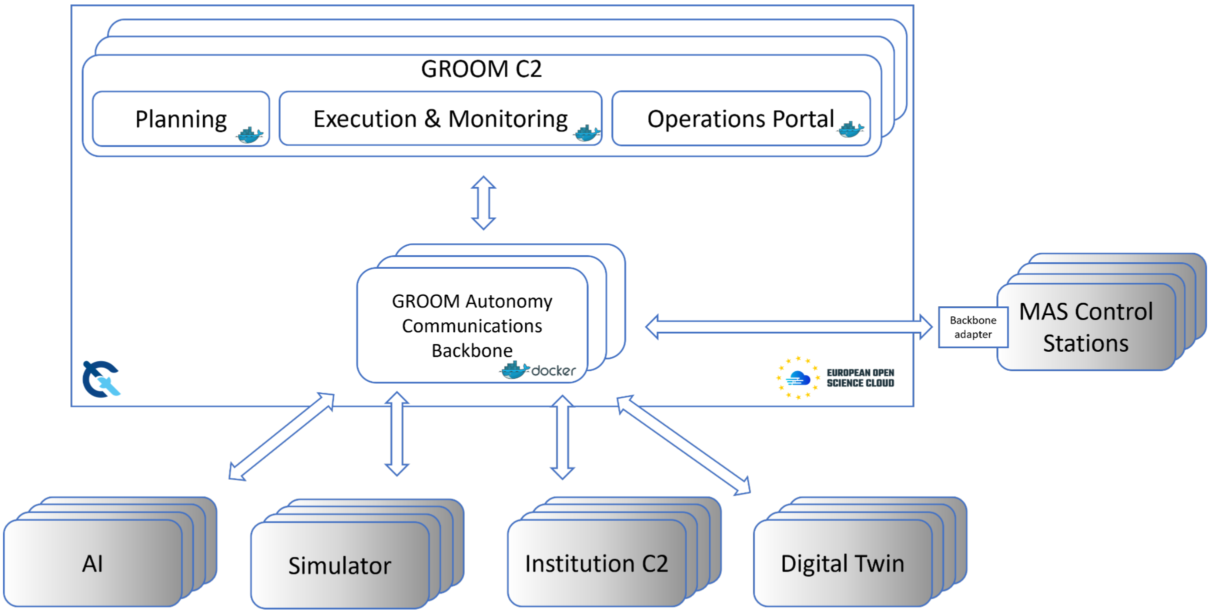

Figure 3 - GROOM Autonomy Ecosystem Architecture

Figure 3 envisions a series of systems (in the middle) developed by the GROOM RI, providing piloting tools and facilitating the integration with other systems developed and maintained outside of the RI (grey boxes).

In the diagram, the grey boxes are part of the GROOM ecosystem but are not necessarily developed and maintained by the GROOM RI. The Autonomy Communication Backbone enables the integration of components to interoperate and communicate while reducing the coupling of systems. Details of the different components are discussed below.

- The **MAS control stations** are owned by institutions that can be part of the GROOM RI. Each institution may have one or many of these. During the FP7 GROOM project, it was theorised that a GROOM RI should centrally host these MAS control stations, providing iridium connection in a single point; this approach can provide some advantages as centralising the maintenance of IT resources and having just one entity consuming satellite communications (Iridium) could help to negotiate better communication rates. We now believe that this approach is currently not achievable nor even realistic; first, the MAS control stations don’t provide a granular access control system, which makes it very difficult to keep a central system with users from multiple organisations even if the number of MAS operated in the ocean observing domain is still small; it is a system that, up to a point, relies on trust that people won’t interfere with other operations. However, even in cases where there is no malicious intent, mistakes can occur if people introduce erroneous commands into different organisational MAS assets. Those are the reasons why we currently believe the MAS control stations must stay in the nodes maintained by them. While the GROOM RI must keep re-evaluating that situation as we believe the hypothesis of the FP7 GROOM was correct, it is just too early for that centralisation to happen.
- **AI** and **simulator systems** are of value for MAS operators as they can help to automate tasks like the generation of waypoints, optimise observations or help to understand the behaviour

of MAS. These are usually complex systems that require deep knowledge of computer science or other academic disciplines to be developed. We envision that the GROOM RI will use these systems routinely (GROOM FP7 have already demonstrated their feasibility), but they won't necessarily be developed directly by the RI. Instead, the GROOM RI must scan the landscape to partner with the best academics and industrial partners in the field to provide access to simulators and AI systems to the GROOM nodes, helping acquire funding and coordinate proposals and projects. As with the previous point in this list, the boundary of what the GROOM RI manages can be a bit fluid, and we envision that in the future, there will be simulators and AI systems that are inside of what the GROOM RI can offer, but for simplicity, these will be kept outside of the core GROOM systems for now.

- As for **Institution C2s,** in the case of an institution working with the GROOM RI, either a node or an external one, would have its own C2, the GROOM RI must facilitate the integration within the GROOM RI systems. The cleanest way to do this is to provide clear interoperability standards.

- The interest and research around **digital twins** have taken off since the GROOM II proposal was created, with flagship initiatives funded by EU programs such as the Horizon Europe Iliad[2] or the EDITO Infra and EDITO ModelLab[3]. These highly sophisticated digital twins of the ocean aim to facilitate understanding a large number of different ocean scenarios. While some of the Iliad demonstrators utilise data from the observing system, we need to be aware of any of them reconfiguring it. GROOM RI can provide the infrastructure to close this loop, allowing Digital Twins to command MAS, effectively reconfiguring the observing system to validate models, generate observations to refine models or help with discovery science activities. Figure 5 illustrates how these interactions are envisioned.

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[2] https://ocean-twin.eu/

[3] https://edito-infra.eu/, https://www.edito-modellab.eu/

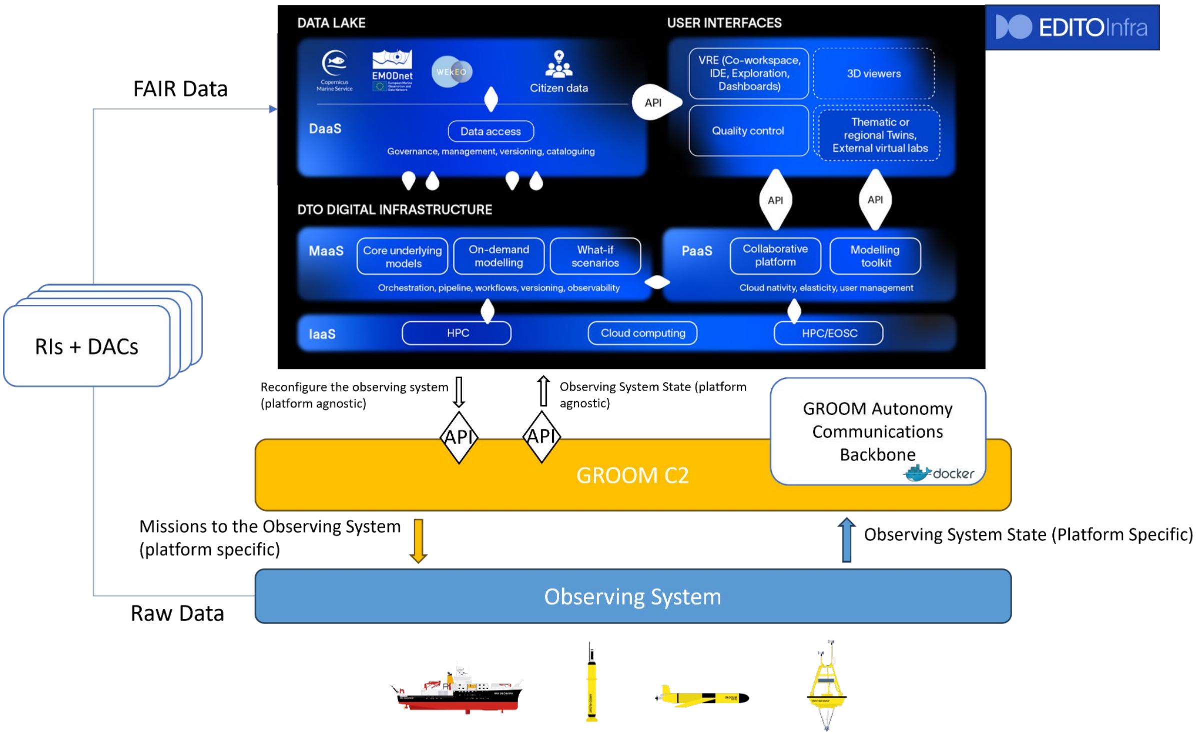

Figure 4 - Envisioned fit of the GROOM RI Autonomy in the context of digital twins

For illustrative purposes, the EDITO Infra architecture was chosen. The DT will operate at the upper layers providing users with what-if scenarios and modelling information. The GROOM C2 and the communications backbone will allow the integration with the observing system.

The Autonomy Communications Backbone is at the centre of the architecture and will allow communications between the different parts of the ecosystem. The backbone will have the following characteristics:

- Be deployable anywhere with minimal modern system requirements, either on a local server of an organisation, a cloud service, or a server in a research ship. Popular containerisation technology such as Docker will be utilised for compatibility;
- Be protocol agnostic. The messages sent through the backbone will be defined independently and bespoke to its particular setup or project;
- Be open source and hosted in GitHub and the European Science Cloud for better accessibility and support;
- Be independently deployed. There won't be a single backbone, and it will be created and destroyed for a particular campaign. Every backbone instance is meant to be short-lived, though it can be customised to support a permanent infrastructure. Less permanent IT infrastructure ensures minimal maintenance, upgrades, and support requirements.

GROOM RI **will create standard messages and protocols** for essential information exchange between system endpoints through the backbone. The message protocol **will be customisable to support mission-specific messages** such as custom sensor payloads or interfaces to a real-time ocean model data assimilation. Some envisioned basic or standard messages will include

- Vehicle status updates describing the vehicle's state (e.g., position, battery, health, etc.). The message format or protocol is intended to be abstract, common to most platforms, but there will be options to send platform-specific information as extra payloads;

- Environmental or observation data updates, with the data captured by MAS sensor payloads (e.g., CTD, wet lab, etc.). Again, this message format is intended to be generic and adhere to widely adopted data standards such as the NetCDF but will allow additional modifications to add and transport mission or platform-specific data. Data centres could also use this for their data integration data flow,

- Mission execution messages containing actions or tasks to be executed by each vehicle or platform,

- Planning messages. This will define high-level mission planning done by humans.

- Human conversations for communications and logging between people involved (e.g., operations team, scientists, principal investigators, etc.).

A GROOM command and control system is the composition of 3 different applications:

- **Mission planning**, or rather, campaign planning, to define areas of operation and the actions each vehicle must execute. This tool will allow the principal investigators (PIs) to generate platform abstract mission plans to be sent to the piloting crew to be reviewed and executed;

- **Mission execution and monitoring** to convert high-level plans to generic vehicle executable plans, send plans to MAS control stations, monitor plan execution for each vehicle, and show the vehicle states or overall MAS status updates;

- The **campaign portal** will show information or the progress of operations to parties involved, scientists, or the general public. The portal also connects campaigns to their data in the Global Data Assembly Centre (GDAC), facilitating data download and information access.

The backbone adapters will connect the MAS proprietary control stations with the backbone and hence with anyone connected. GROOM RI should incentivise the creation and open-sourcing of these adapters.

The centralised communication link through the adapters provides an architecture adaptable to various use cases or project-specific objectives, enabling better collaborations between organisations. The modularity of the design ensures that each instance of the architecture, whether for a short-term deployment or a long-term core piloting infrastructure, is:

- **Scalable**, in terms of ease of adding new features, capabilities, or MAS platforms to the system;

- **Replicable**, for example, in case of IT system reset or downtime;

- **Repeatable** for system validation exercises or scientific modelling verification experiments in a real-world or simulated environment;

- **Reliable**, by adding redundancies or isolating core components to remove single-point-of-failures.

Recommendation [3]: GROOM RI must design an open autonomy ecosystem to allow scaling up autonomy.

Recommendation [4]: GROOM RI must push international standards to enable the interoperability and integration of MAS C2 systems, collaborating with important non-academic players in this field, such as CMRE or industrials like CLS.

Our design will:

1. Help integrate new AI and automation systems, providing consistent interfaces to connect developers of those systems with the MAS control stations.
2. Help with the sharing of piloting between organisations, as it will enable the interconnection of the different MAS control stations and the adoption of a common C2 solution for the monitoring and execution of plans, allow the geographical distribution of piloting tasks between teams, as the digital backbone will severely reduce the complexity of connecting different organisations.

Each part of the architecture is envisioned to be able to run containerised and standalone, not requiring them to run 24/7, just being deployed when required for particular campaigns. To facilitate smaller partners' usage and reduce the DevOps required, the GROOM RI autonomy architecture can be set up to be easily deployed as a service in the European Science Cloud.

Recommendation [5]: GROOM RI must develop all the autonomy ecosystems as individual containerised solutions that can be used standalone.

Recommendation [6]: GROOM RI must develop the autonomy ecosystem in a way it is easy to deploy and use by non-DevOps users; for example, a non-expert user should be able to deploy the systems as services in the EOSC with a couple of clicks.

Recommendation [7]: GROOM RI will become an EOSC provider of digital services.

3.2 - Implementation

The GROOM Autonomy is an ambitious architecture; building it will require expert software development and robotics knowledge. The good news is that GROOM does not need to start from scratch; there are already some solutions built by some of the GROOM II partners that cover part of the designed architecture, and while they are not ready to be the GROOM solution, they would save time of development and money. The most mature solutions are the UPorto LSTS Toolchain and the NOC Command and Control. The UPorto system is currently Open Source and has been successfully used in real AUV operations for more than ten years. The shortcomings are that it still requires some knowledge of the LSTS toolchain to know how to run it, and the features are mainly focused on traditional AUVs, and not on long-range platforms. NOC C2 is, on the other hand, well-suited and designed for long-range operations, and the UPorto solution requires a lot of know-how from NOC engineers to run it. Another current obstacle is that NOC C2 is not open-source, but NOC has the will to open-source components and share them with the GROOM community. Both systems have also been designed for specialised users, which would need adequate interfacing for access by the users of the GROOM RI.

The LSTS toolchain development started twenty years ago, and NOC C2 development in 2016. If we add up the resources invested in both systems in terms of money, we would get numbers above several million euros. Would the development of the GROOM autonomy ecosystem cost that much? The answer is no if people with the right knowledge are involved. However, assembling a software engineering team and starting the process from zero would still require significant resources.

Recommendation [8]: GROOM RI should amalgamate the existing expertise and know-how from the LSTS Toolchain and NOC C2 ecosystem and use them as the base of the new GROOM RI infrastructure with its RI user-oriented philosophy.

Developing and implementing the ecosystem will be complex and must be done in iterative phases.

A rough working plan has been elaborated to give an idea of how much this could cost and how long it could take. This will give reviewers an idea of the feasibility of developing the GROOM RI autonomy ecosystem.

The work was designed in two phases: in phase 1, an engineering team must be assembled. For this type of work, it would be optimal to have a team of five or six software engineers for the squad, plus a team manager and if using Scrum as methodology, a product owner and a Scrum master.

A detailed design plan must be outlined:

1. Development methodology. We encourage the team to follow an iterative process guided by AGILE[4] principles;
2. Development stack. This will depend highly on the engineering team and whether the new solution is based on the LSTS and NOC systems;
3. Detail architecture design;
4. Set up version control platforms (GitHub, GitLab…), testing, and continuous integration facilities (Jenkins, GitLab ci, GitHub runners …).

This phase should last **one year** of highly intensive work, considering a 100% allocation of the squad and 50% allocation of the team manager and/or product owner.

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[4] https://agilemanifesto.org/

During Phase 2, the first implementation step will involve developing and implementing the backbone and backbone adapters. These critical components will receive and decode inputs from various sources. Implementing these components allows the system to integrate data from different sources, providing a comprehensive view of the overall system. This will be a significant milestone in the implementation process, enabling the system to handle a wide range of inputs and operate at scale. During phase 2, the operation of the backbone and its associated components will be demonstrated. This will involve rigorous testing of the backbone's ability to integrate data from different sources and transmit it to other system components. The performance and reliability of the backbone will be closely monitored and evaluated to ensure that it meets all functional requirements and can operate effectively under a range of conditions. This phase will be critical in **demonstrating** the feasibility and potential of the overall system and will be an essential milestone in the implementation process. By demonstrating the effective operation of the backbone and associated components, the team will gain valuable insights into the system's performance and identify any areas for improvement.

Phase 3 will focus on the development and implementation of the C2, with a particular focus on its execution and implementation. This phase will include a **second demonstration** of the backbone and C2 in operation. During this phase, the team will work on integrating the C2 with the backbone, allowing it to control and coordinate the various components of the system. The C2 will be tested extensively to ensure it can effectively manage the system's operations and respond to changing conditions. By demonstrating the integration of the backbone and C2, the team will be able to show how the system can operate at scale and handle a range of inputs and outputs. This phase will be critical in refining and optimising the overall system architecture, allowing the team to identify any areas for improvement and refine the system's design.

Phase 4 will focus on developing and implementing additional components of the C2 system, specifically the planning tool and public portal. This phase will include a **third demonstration** of the software developed during the previous phases. The planning tool will help operators manage and coordinate the system's operations, allowing them to make informed decisions based on real-time data. The public portal, on the other hand, will provide stakeholders with access to the system's data and performance metrics, promoting transparency and accountability. The development and integration of these components will be a critical step in realising the system's full potential, allowing it to operate efficiently and effectively under a range of conditions. The team will work closely to ensure that these components are rigorously tested and meet all functional requirements, and any issues or bugs will be addressed promptly. The team can showcase the system's capabilities and potential for real-world applications by demonstrating the complete system with all components in operation.

Phase 5 is the project closure, where the majority of the work is over, but it remains important to measure the success of the GROOM RI. This involves determining if the project goals were met and if the initial problem was solved, and evaluating the partner's performance and quality of work. It also implies documenting the project learnings, ensuring that all the aspects of the project are completed without any issues unsolved and handing over final deliverables to key stakeholders.

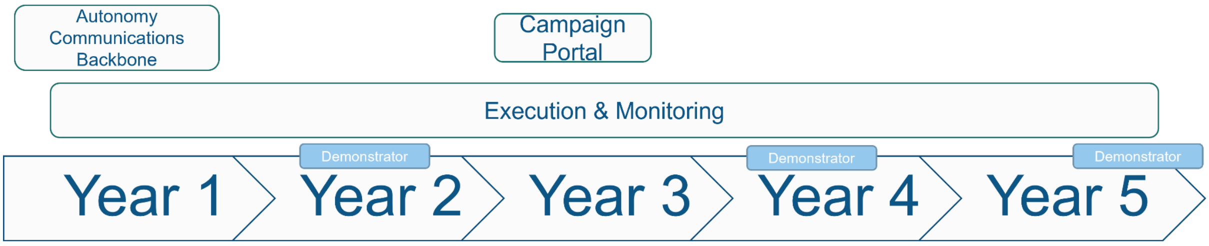

Figure 5 - This is a speculative plan of work to deliver the Core system

This is an illustrative example of what it would take to develop the system. Once the system is handed over to an operational phase, the long-term operational costs need to be considered.

4. Conclusion and Recommendations

Multiple organisations across Europe have been successfully operating MAS for years, but the current approach has scalability problems; sharing resources is partially limited by technology as it is the development of automation. Most organisations need to be bigger to develop and maintain the cyberinfrastructure required to change capability and leverage AI systems. With the European RI landscape in continuous evolution, the future GROOM RI can fill gaps that people may not even realise exist; having an actor coordinating efforts to increase MAS and MAS C2 interoperability is fundamental to enable the development of collaborative systems. GROOM RI will act as the glue to implement the next generation of systems integrating MAS and accelerating the use in observing systems.

This design study provides a vision and a disruptive and innovative design of what this autonomous ecosystem can be. We have provided an estimation of how we can start to implement the ecosystem, with the hope that will bring anyone reading this report a feeling of how ambitious this task is.

Recommendation [1]: GROOM RI must create a Cyber Infrastructure and Command and Control Working group.

Recommendation [2]: GROOM RI must find sustained funding to deliver a community-driven command and control ecosystem.

Recommendation [3]: GROOM RI must design an open autonomy ecosystem to allow scaling up autonomy.

Recommendation [4]: GROOM RI must push international standards to enable the interoperability and integration of MAS C2 systems, collaborating with important players in this field such as CMRE.

Recommendation [5]: GROOM RI must develop all the autonomy ecosystems as individual containerized solutions that can be used standalone.

Recommendation [6]: GROOM RI must develop the autonomy ecosystem in a way it is easy to deploy and use by non-DevOps users; for example, a non-expert user should be able to deploy the systems as services in the EOSC with a couple of clicks.

Recommendation [7]: GROOM RI to become an EOSC provider of digital services.

Recommendation [8]: GROOM RI should amalgamate the existing expertise and know-how from the LSTS Toolchain and NOC C2 ecosystem and use them as the base of the new GROOM RI infrastructure with its RI user-oriented philosophy.

Recommendation [9]: GROOM RI must demonstrate the added value to communities with demonstrators of coordinated multi-institution deployments of MAS operated using the GROOM community tools.

5. References

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[4] von Oppeln-Bronikowski, N., Zhou, M., Bahadory, T. and de Young, B., 2021. Overview of a new ocean glider navigation system: OceanGNS. Frontiers in Marine Science, 8, p.671103.

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Appendix 1 - Piloting tools

This section describes the current state of the art on piloting. This is an update on the work done on the FP7 GROOM. It then describes solutions created by groups within the glider community and how they advance the state of the art.

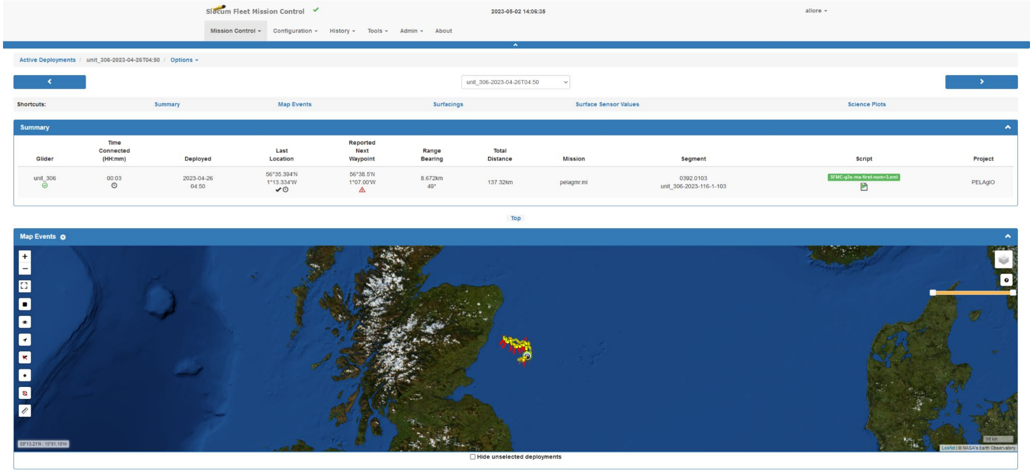
Manufacturer tools

The current status of piloting tools for gliders and AUVs is marked by significant progress in recent years. These tools, including advanced algorithms, sensors, and communication systems, have enabled these uncrewed underwater vehicles to operate autonomously, navigate accurately, and collect data efficiently.

Gliders have piloting tools optimised for gliding performance, including strategies for buoyancy control, pitch adjustment, and glide path optimisation. AUVs, on the other hand, are equipped with sophisticated piloting tools that enable obstacle avoidance, precise positioning. While these piloting tools have evolved to allow for longer missions, improved navigation, and efficient data collection, challenges still exist.

SFMC/Dockserver (Slocum)

This is Teledyne's Webb Research (TWR) Slocum glider C2. It provides a web interface with the dockserver which interacts with the gliders. It allows a group of pilots to manage and pilot several gliders. Slocum users have the option to run their own instance of SFMC or to pay for it as a hosted service from TWR. SFMC now includes a REST API to allow users to automate some glider activities. A relatively simple access rights system is provided, allowing basic interaction within the steering team.



Glider	Time Connected (HH:mm)	Deployed	Last Location	Reported Next Waypoint	Range Bearing	Total Distance	Mission	Segment	Script	Project
unit_306	00:03	2023-04-26 04:50	56°35.394'N 1°13.334'W	56°38.5'N 1°07.00'W	8.672km 49°	137.32km	pelagmr.mi	0392.0103 unit_306-2023-116-1-103	SFMC-g3s-ma-first-num-3.xml	PELAgIO

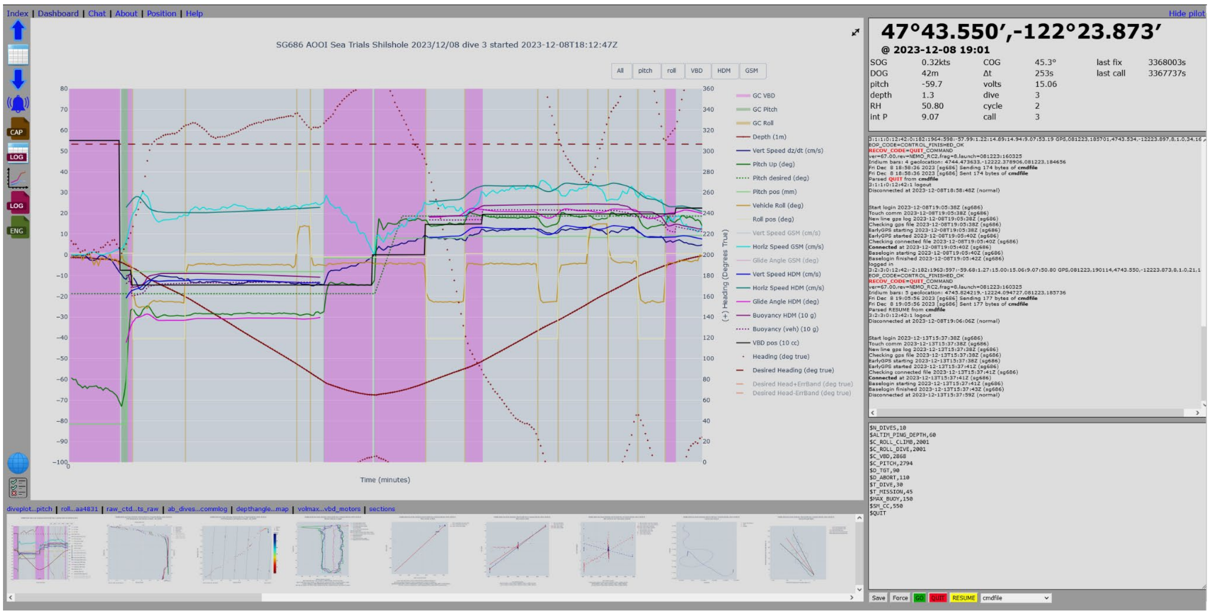
☐ Hide unselected deployments

Figure 6 - Teledyne's Webb Research (TWR) Slocum glider C2

Basestation/SG piloting tools (Seaglider)

The Seaglider piloting is done through a server (base-station), in which an open-source set of Python code is installed, and with pilots connecting to it using SSH (in the simplest approach.) Gliders connect and a transfer of files happens both ways, with control files going to the glider and technical and science files coming to shore. From here, some operators download those data files into their computer and use a series of Matlab scripts or a Matlab executable to interpret the data and make piloting decisions. Pilots manually modify the control files directly or upload them to the base station. Other operators have built web interfaces to display and send data.

In 2023, the Applied Physics Laboratory, University of Washington released a new set of code that extends the existing code by including a powerful front-end GUI for advanced viewing, analysing and sending of glider information. It also includes an improved back end for more advanced flight model evaluation and automatic flight adjustments, technical data analytics, and dynamic plotting tools[5]. An instance of basestation3 has been installed, tested, and operated by Cyprus Subsea, requiring typical IT expertise and minimal troubleshooting. Subscribers only pay for airtime and a fee for the maintenance of server infrastructure.



47°43.550′,-122°23.873′

@ 2023-12-08 19:01

SOG	0.32kts	COG	45.3°	last fix	3368003s
DOG	42m	Δt	253s	last call	3367737s
pitch	-59.7	volts	15.06		
depth	1.3	dive	3		
RH	50.80	cycle	2		
int P	9.07	call	3		

```
3:1:1:0:12:42:0:182:1964:598:-57.99:1.22:14.89:14.94:9.07:53.19 GPS,081223,185701,4743.534,-12223.897,8,1.0,34.16
EOP_CODE=CONTROL_FINISHED_OK
RECOV_CODE=QUIT_COMMAND
ver=67.00,rev=NEMO_RC2,frag=8,launch=081223:160325
Iridium bars: 4 geolocation: 4744.473633,-12222.378906,081223,184656
Fri Dec  8 18:58:36 2023 [sg686] Sending 174 bytes of cmdfile
Fri Dec  8 18:58:36 2023 [sg686] Sent 174 bytes of cmdfile
Parsed QUIT from cmdfile
3:1:1:0:12:42:1 logout
Disconnected at 2023-12-08T18:58:48Z (normal)


Start login 2023-12-08T19:05:38Z (sg686)
Touch comm 2023-12-08T19:05:38Z (sg686)
New line gps log 2023-12-08T19:05:38Z (sg686)
Checking gps file 2023-12-08T19:05:38Z (sg686)
EarlyGPS starting 2023-12-08T19:05:38Z (sg686)
EarlyGPS started 2023-12-08T19:05:40Z (sg686)
Checking connected file 2023-12-08T19:05:40Z (sg686)
Connected at 2023-12-08T19:05:40Z (sg686)
Baselogin starting 2023-12-08T19:05:40Z (sg686)
Baselogin finished 2023-12-08T19:05:42Z (sg686)
logged in
3:2:3:0:12:42:-2:182:1963:597:-59.68:1.27:15.00:15.06:9.07:50.80 GPS,081223,190114,4743.550,-12223.873,8,1.0,21,1
EOP_CODE=CONTROL_FINISHED_OK
RECOV_CODE=QUIT_COMMAND
ver=67.00,rev=NEMO_RC2,frag=8,launch=081223:160325
Iridium bars: 5 geolocation: 4745.824219,-12224.094727,081223,185736
Fri Dec  8 19:05:56 2023 [sg686] Sending 177 bytes of cmdfile
Fri Dec  8 19:05:56 2023 [sg686] Sent 177 bytes of cmdfile
Parsed RESUME from cmdfile
3:2:3:0:12:42:1 logout
Disconnected at 2023-12-08T19:06:06Z (normal)


Start login 2023-12-13T15:37:38Z (sg686)
Touch comm 2023-12-13T15:37:38Z (sg686)
New line gps log 2023-12-13T15:37:38Z (sg686)
Checking gps file 2023-12-13T15:37:38Z (sg686)
EarlyGPS starting 2023-12-13T15:37:38Z (sg686)
EarlyGPS started 2023-12-13T15:37:41Z (sg686)
Checking connected file 2023-12-13T15:37:41Z (sg686)
Connected at 2023-12-13T15:37:41Z (sg686)
Baselogin starting 2023-12-13T15:37:41Z (sg686)
Baselogin finished 2023-12-13T15:37:43Z (sg686)
Disconnected at 2023-12-13T15:37:59Z (normal)
```

```
$N_DIVES,10
$ALTIM_PING_DEPTH,60
$C_ROLL_CLIMB,2001
$C_ROLL_DIVE,2001
$C_VBD,2868
$C_PITCH,2794
$D_TGT,90
$D_ABORT,110
$T_DIVE,30
$T_MISSION,45
$MAX_BUOY,150
$SM_CC,550
$QUIT
```

Figure 7 – Base-station 3 Dashboard GUI

As illustrated in Figure 7, operators can review all relevant engineering plots to command a seaglider. The GUI allows the modification of waypoints or any other Seaglider parameter.

Glimpse (SeaExplorer)

Glimpse is the service provided by Alseamar to pilot the SeaExplorer. It is a complete solution hosted on Alseamar servers, very similar to the above systems. Presently, users don't have the option to run their own instance of Glimpse and must pay a fee for the service hosted by Alseamar.

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[5] (https://github.com/iop-apl-uw/basestation3

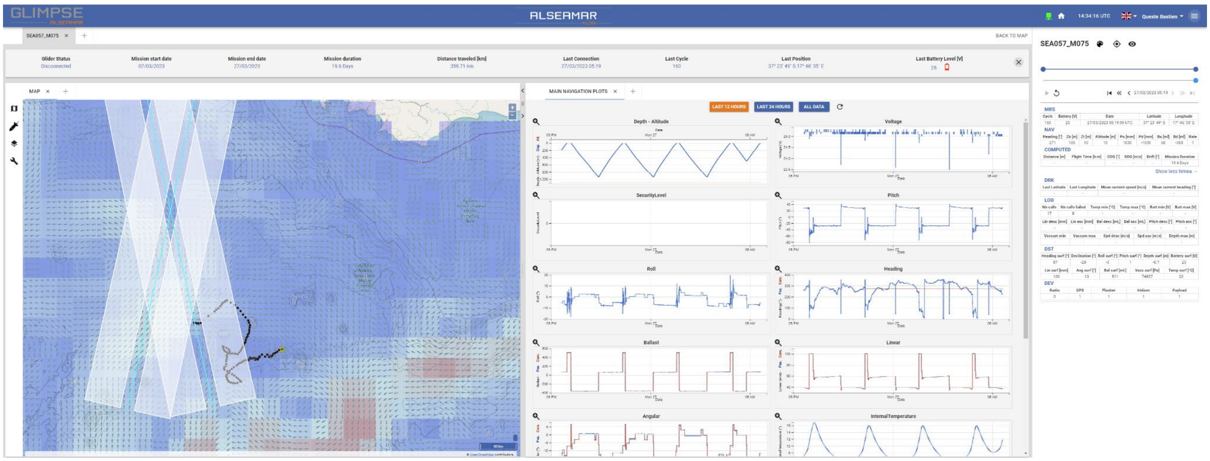

Figure 8 - Glimpse by Alseamar

Non-manufacturer tools

Description of some relevant systems and tools to operate MAS developed by organisations and communities.

EGO Glider Fleet Control Panel (GFCP)

Developed by CNRS-INSU (FR) this was the first attempt to create a glider C2 at the European Glider Observatories[6] (EGO) community scale, which started in 2006. This work was a contribution to the EGO COST Action where several community tools were envisaged and developed as early prototypes. The solution was branded under the EGO label, widening the utilisation to more groups beyond France across Europe and even more widely. The GFCP provides a web interface to glider operators, helping to share piloting between organisations and remote sites. The system works with Slocums, Seagliders, and Sprays. The GFCP runs on servers managed by CNRS-INSU, synchronising files with the glider control stations (so-called dockserver, basestation) of the different organisations using the GFCP.

Some basic relevant features included in the GFCP:

- A general web interface to map and manage the glider activity across multiple organisations. The mapping is shared with the OceanOPS WMO support centre;
- Web editor to allow pilots to modify the glider control files on the server and transmission to the glider control stations with logging of all commands sent to the gliders;
- A mission logbook allowing the operators to leave messages to other members of the piloting crew or to do operation handovers.

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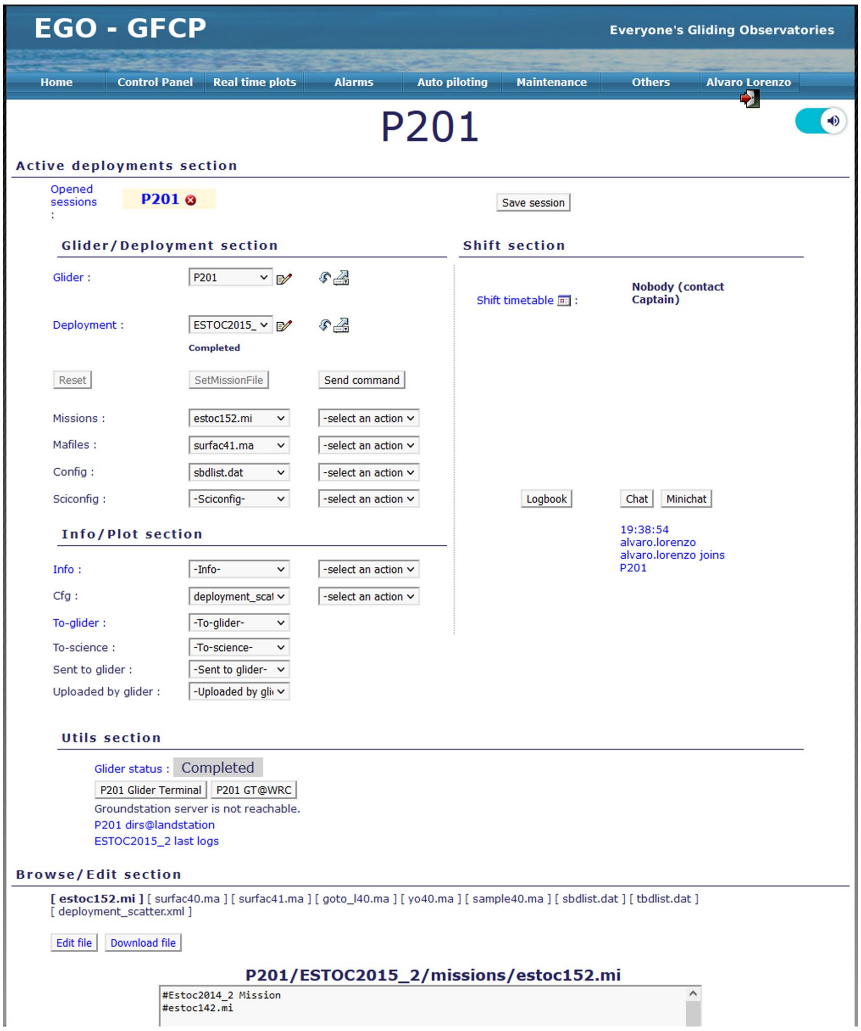
[6] During a meeting in Larnaca (Cyprus) in 2009, EGO became later Everyone's Glider Observatories, to include the global glider operators and scientists.

- A shift planning tool to allow organising a piloting crew from multiple organizations with hierarchical roles;
- Map plots showing glider trajectories including the depth-averaged currents and surface drifts, as well as engineering and scientific data plots;
- Customizable SMS notifications to report warnings and alarms.

The GFCP was further developed to include more advanced features. First, a maintenance system was added, allowing to follow the history of each glider component and sensor, with an "instantiation" feature when a mission was assigned to the glider. The instantiation allows the trigger of multiple actions such as the automated generation of the metadata at the EGO format for the Data Assembly Center (DAC), automated transfer to the DAC, and generation of plots for a fleet. Secondly, an "automated piloting" feature was also developed. It allows to speed up /slow down a glider according to criteria, switch on/off the altimeter regarding bathymetry and similar features. A fully automated generation of the waypoints for a glider fleet taking into account the ocean currents with the computation of their "Lagrangian Coherent Structures" (LCS) from satellite altimetry or Copernicus models was also tested. These automated features are no longer supported. Finally, an advanced mission simulation using real-time multi-model Copernicus forecasts provided support to the pilots to optimise the mission over a week. This simulator is no longer supported.

The GFCP is still a visionary designed series of software in the perspective of an international shared infrastructure for glider piloting and is still anticipating the GROOM C2. However, it has not been developed with modern programming standards allowing modularity, easy maintenance, evolution and wide distribution as a package.



P201

Active deployments section

Opened sessions : P201

Glider/Deployment section

Glider : P201

Deployment : ESTOC2015_

Completed

Missions : estoc152.mi -select an action

Mafiles : surfac41.ma -select an action

Config : sbdlist.dat -select an action

Sciconfig : -Sciconfig- -select an action

Shift section

Shift timetable : Nobody (contact Captain)

19:38:54
alvaro.lorenzo
alvaro.lorenzo joins P201

Info/Plot section

Info : -Info- -select an action

Cfg : deployment_scat -select an action

To-glider : -To-glider-

To-science : -To-science-

Sent to glider : -Sent to glider-

Uploaded by glider : -Uploaded by gli

Utils section

Glider status : Completed

Groundstation server is not reachable.
P201 dirs@landstation
ESTOC2015_2 last logs

Browse/Edit section

[estoc152.mi] [surfac40.ma] [surfac41.ma] [goto_l40.ma] [yo40.ma] [sample40.ma] [sbdlist.dat] [tbdlist.dat]
[deployment_scatter.xml]

P201/ESTOC2015_2/missions/estoc152.mi

```
#Estoc2014_2 Mission
#estoc142.mi
```

Figure 9 - EGO Glider Fleet Control Panel (GFCP) landing page.

Figure 9 shows the EGO Glider Fleet Control Panel (GFCP) landing page once the user has logged in. The UI allowed pilots to easily select the platform and mission configurations to pilot.

NOC C2

The UK National Marine Equipment Pool (NMEP) includes a wide range of autonomous vehicles, with different capabilities, constraints, and operating procedures. At present, each of these systems has its own command and control interface, requiring an experienced operator to supervise individual vehicles during a deployment. This creates a bottleneck, restricting the number of vehicles that can be deployed simultaneously, which reduces the complexity of missions and our ability to react to large-scale evolving features, such as algal blooms. The current complexity of the piloting process also restricts the ability of the science end-user or Principal Investigator (PI) to directly engage with the control and calibration of the remote vehicle.

A Unified Piloting Framework. With growing demand, both in the number and the complexity of vehicle deployments, these issues will become an ever-greater challenge. To address this, as part of Oceanid's £16M NERC investment into Marine Autonomy at NOC, a unified command, control, and data infrastructure is developed to enable near real-time data access and remote operation of the NMEP long-range fleet.

The Unified Piloting Framework has been designed as a collection of microservices to receive and process data from, and compile and transmit commands to the various platform types with the NMEP. The modularity of the architecture allows additional platform types to be easily integrated into the framework.

The C2 Web Interface. In addition to the Unified Piloting Framework, a command and control (C2) [1] web interface has been developed to allow pilots to monitor the vehicles in near real-time through a single interface and to update a vehicle's configuration throughout their deployments.

The interface has been designed around a set of common pages:

- The Health page displays the current status of the vehicle with positions and events from the deployment;
- The Science page includes interactive plots containing the data collected from the science sensors;
- The Plan page allows users to plan agnostic behaviour-based missions, which can then be sent to the vehicle;
- The Files and Terminal pages allow the user to download data received from the vehicle and control the vehicles.

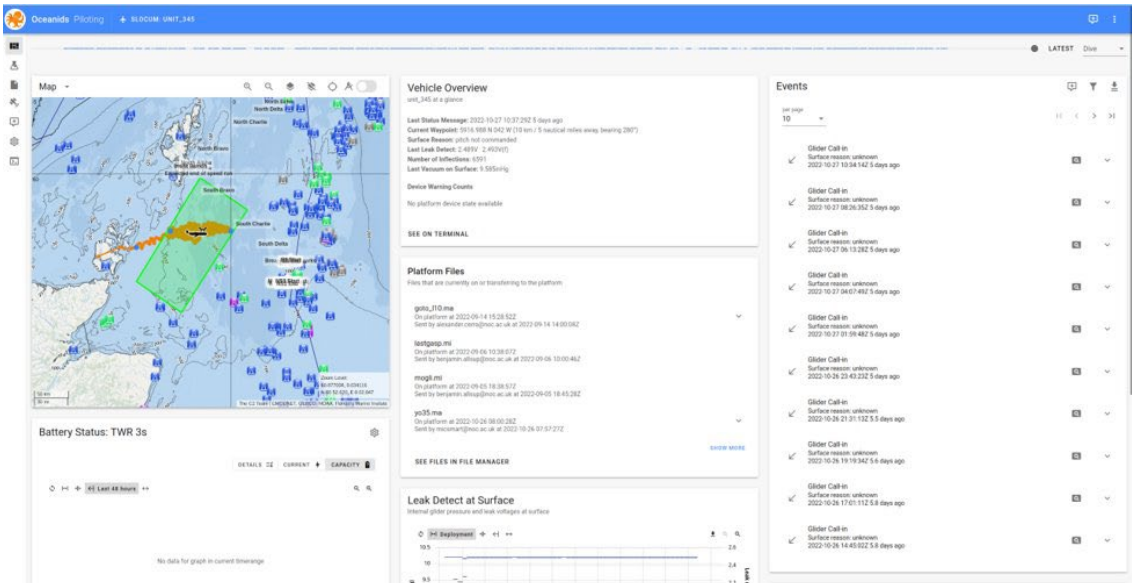


Figure 10 - Piloting Dashboard: Shows the relevant information for piloting.

Figure 10 shows custom based information depending on the type of MAS.

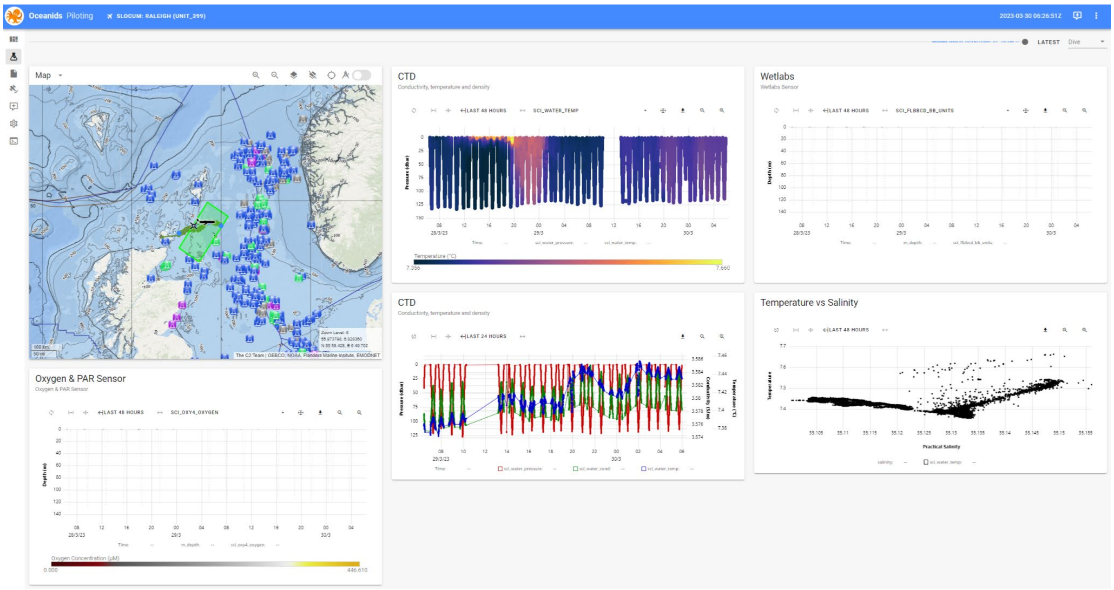
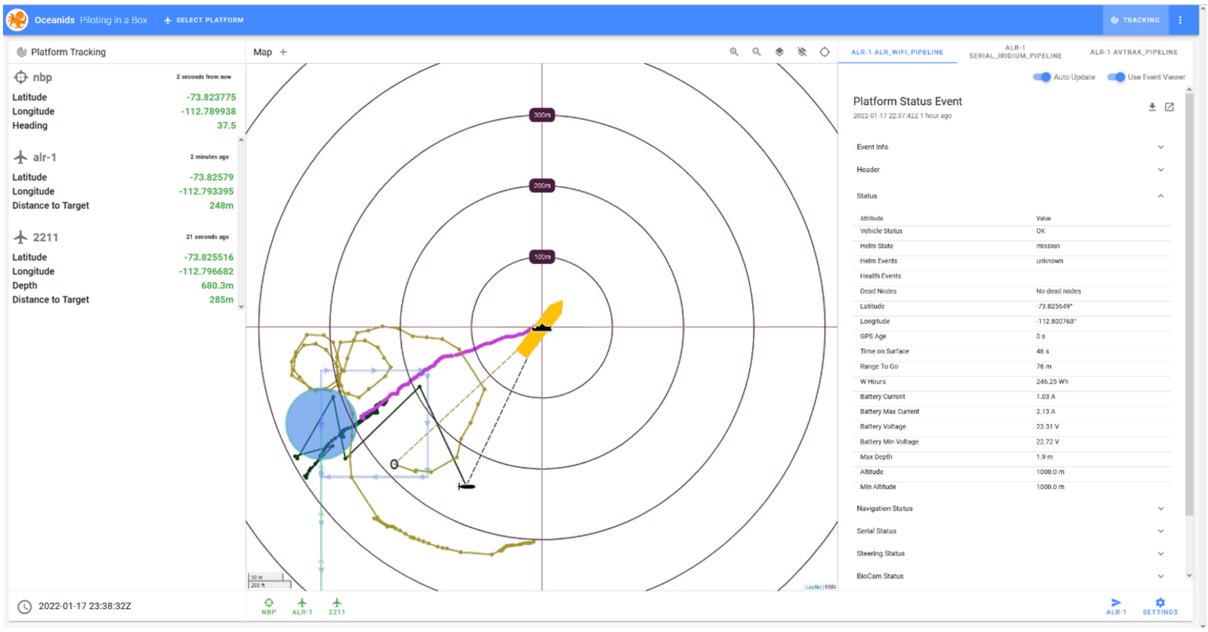


Figure 11 - Science Monitoring: Allows to dig into the data coming from the platform.

Operational Use. Since development began in 2017 the framework is now operational with over 50 active users from several groups (NOC, BODC, BAS, UEA, PML and SAMS). It has become our daily operational tool for the majority of NMEP glider piloting, as well as being the primary interface for the planning and monitoring of our in-house Autosub Long Range vehicles.

The amalgamation of the various tools into a single interface has decreased the requirements for specialised software and expert-level knowledge for each platform. The times and steps required to carry out regular checks have also been decreased. This means pilots can look after more vehicles and vehicles of multiple types at the same time. The inclusion of authentication and auditing in the interface has opened up the piloting process to significantly more stakeholders, allowing authorised PIs, scientists, and engineers to maintain oversight and adjust the direction of a mission in response to collected data. A contextual logging system allows users to create a log that will be assigned a series of tags depending on the current application context. This, along with logging of interactions with each platform and the ability to view vehicles at a given point in time allows for fault analysis to be carried out from within the interface.



nbp 2 seconds from now

Latitude	-73.823775
Longitude	-112.789938
Heading	37.5

alr-1 2 minutes ago

Latitude	-73.82579
Longitude	-112.793395
Distance to Target	248m

2211 21 seconds ago

Latitude	-73.825516
Longitude	-112.796682
Depth	680.3m
Distance to Target	285m

2022-01-17 23:38:32Z

Platform Status Event
2022-01-17 22:37:42Z 1 hour ago

Event Info
Header
Status

Attribute	Value
Vehicle Status	OK
Helm State	mission
Helm Events	unknown
Health Events	
Dead Nodes	No dead nodes
Latitude	-73.825649°
Longitude	-112.800763°
GPS Age	0 s
Time on Surface	46 s
Range To Go	76 m
W Hours	246.25 Wh
Battery Current	1.03 A
Battery Max Current	2.13 A
Battery Voltage	23.31 V
Battery Min Voltage	22.72 V
Max Depth	1.9 m
Altitude	1000.0 m
Min Altitude	1000.0 m

Navigation Status
Serial Status
Steering Status
BioCam Status

Figure 12 - NOC C2 in a box Real-Time time vehicle tracking.

LSTS Neptus

Neptus [2] is a distributed command, control, communications, and intelligence framework for operations with networked vehicles, systems, and human operators. It can operate all types of unmanned vehicles: unmanned aerial vehicles, autonomous surface, underwater vehicles, and teleoperated ROVs, among others. Neptus system is part of the LSTS-Toolchain for Autonomous Vehicles. The LSTS-Toolchain is composed of four main components:

- **Dune:** This is the onboard software running on the vehicle, which is responsible not only for every interaction with sensors, payload, and actuators but also for communications, navigation, control, manoeuvring, plan execution, and vehicle supervision; **Neptus:** Distributed Command and Control Infrastructure for operating multiple autonomous heterogeneous vehicles;
- **IMC:** Common control message, a transport-agnostic binary protocol used by all LSTS toolchain components for inter-module and intra-module communications;
- **Ripples:** Cloud-based software that concentrates and disseminates data from multiple sources and controls different asset types, as well as providing simplified web interfaces for following and controlling the operations using a browser.

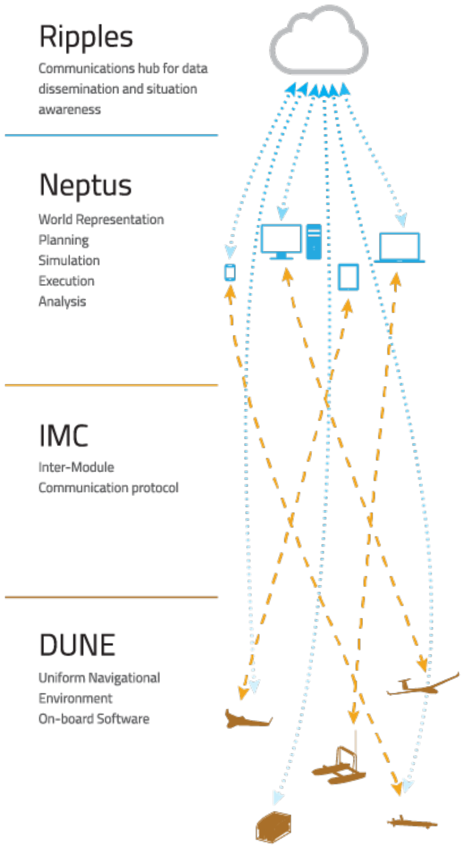


Figure 13 - LSTS Toolchain

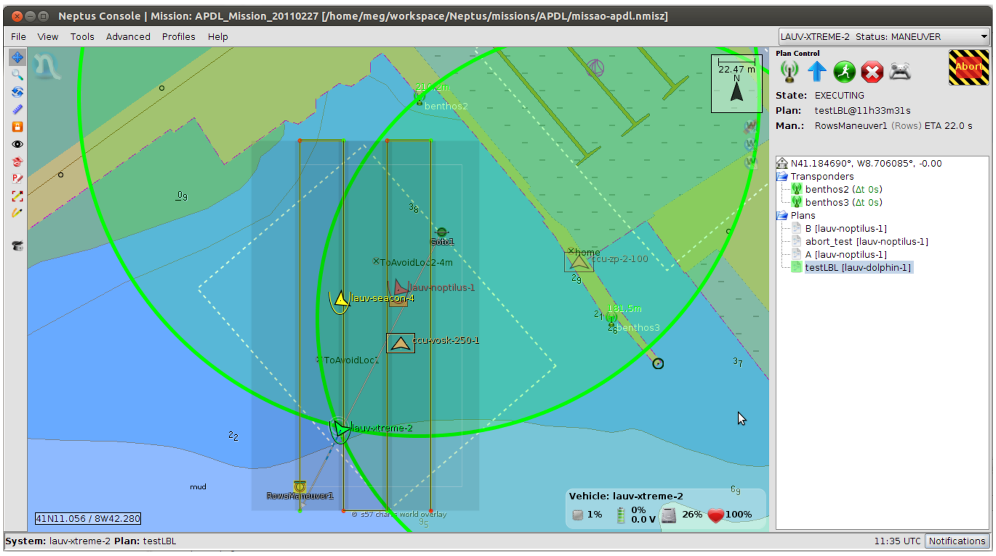
This Neptus distributed architecture is service-oriented, which enables high degrees of interoperability between applications, scalability (number of nodes), and reconfiguration (number and type of nodes).

Inter-Module Communication (IMC) is the main communication protocol for this Command and Control (C2) system, making it interoperable with any other IMC-based peer.
Neptus provides a coherent visual interface to command all these assets, despite the heterogeneity of the controlled systems.

Neptus supports the different phases of a typical mission life cycle: planning, simulation, execution, and post-mission analysis.

Planning. The planning phase is generally performed before executing a mission, and Neptus supports planning for different vehicle types. With the missions, operator objectives must have additional geographical information to be aware of possible obstacles, depth, tide, and marine traffic, among others.

With all this, the operator can choose the best location for command, communication, and location aids and then prepare the mission plans. Plans can be simulated and validated before execution according to the vehicle profile (manoeuvring specifications, sensors, battery, etc.).



LAUV-XTREME-2 Status: MANEUVER

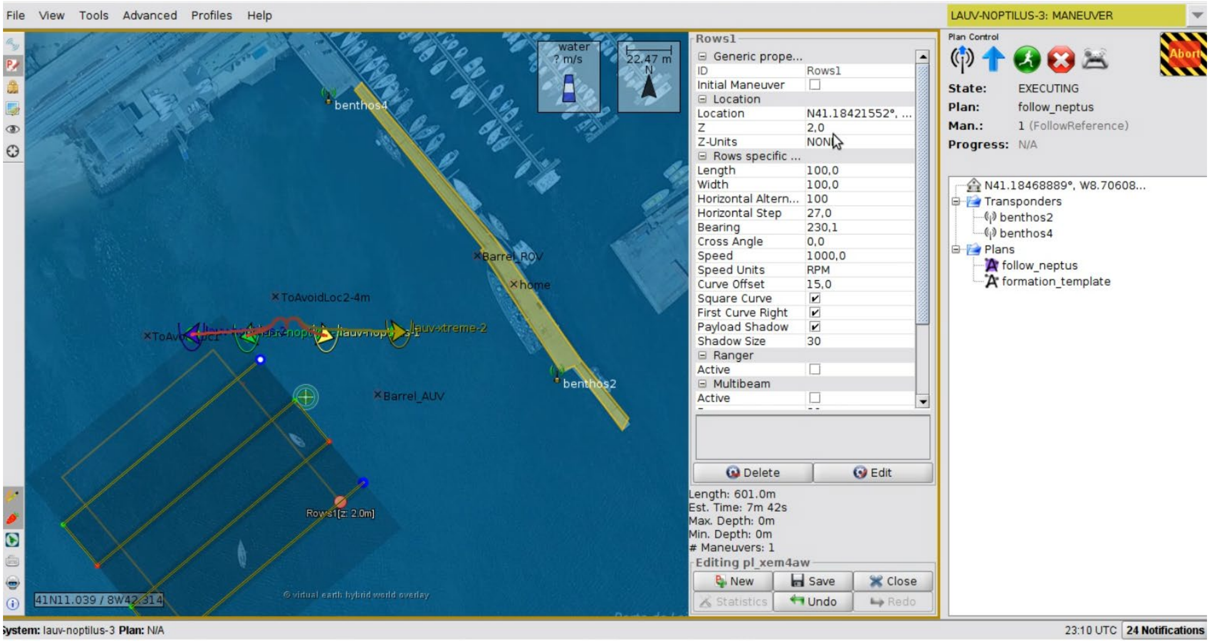
State: EXECUTING
Plan: testLBL@11h33m31s
Man.: RowsManeuver1 (Rows) ETA 22.0 s

N41.184690°, W8.706085°, -0.00
Transponders
  benthos2 (Δt 0s)
  benthos3 (Δt 0s)
Plans
  B [lauv-noptilus-1]
  abort_test [lauv-noptilus-1]
  A [lauv-noptilus-1]
  testLBL [lauv-dolphin-1]

System: lauv-xtreme-2 **Plan:** testLBL

Figure 14 - Neptus (Planning)

Execution. In the execution phase, Neptus can monitor systems telemetry, visualize incoming real-time data from multiple vehicles, teleoperate individual vehicles, and execute/adapt the mission plans. The expected behaviour of vehicles disconnected is simulated so that the user gets a comprehensive, quick glimpse of the state of the entire network.



Rows1

Generic prope...	
ID	Rows1
Initial Maneuver	☐
Location	
Location	N41.18421552°, ...
Z	2,0
Z-Units	NONE
Rows specific ...	
Length	100,0
Width	100,0
Horizontal Altern...	100
Horizontal Step	27,0
Bearing	230,1
Cross Angle	0,0
Speed	1000,0
Speed Units	RPM
Curve Offset	15,0
Square Curve	☑
First Curve Right	☑
Payload Shadow	☑
Shadow Size	30
Ranger	
Active	☐
Multibeam	
Active	☐

Length: 601.0m
Est. Time: 7m 42s
Max. Depth: 0m
Min. Depth: 0m
Maneuvers: 1
Editing pl_xem4aw

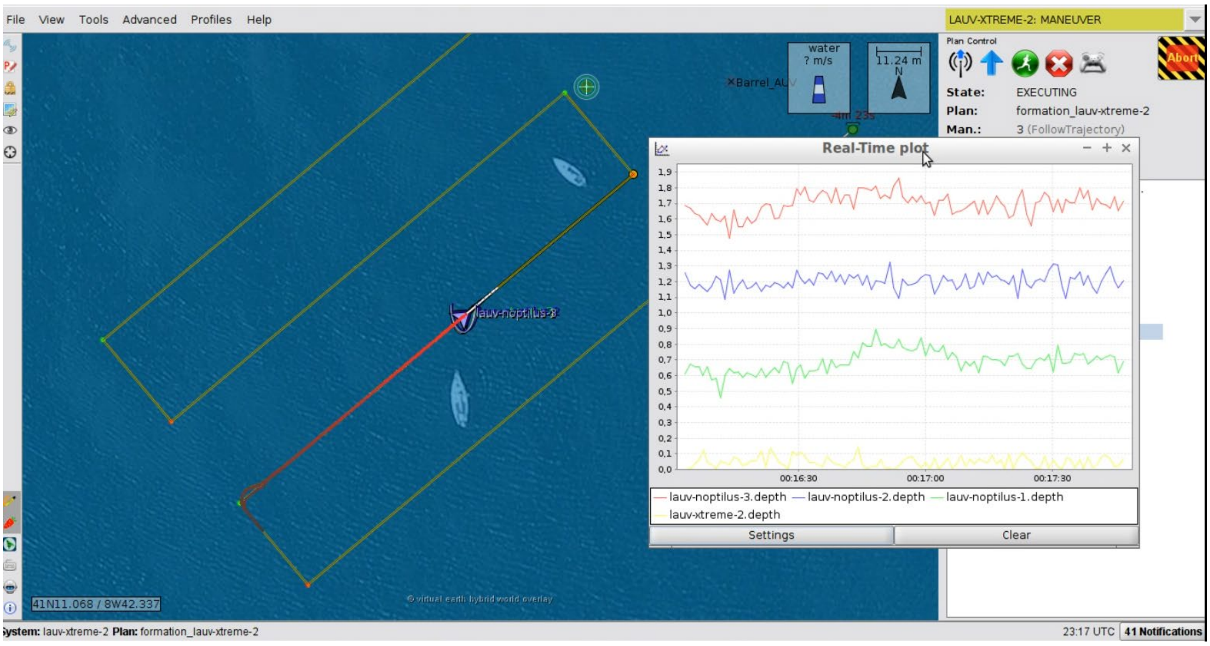
LAUV-NOPTILUS-3: MANEUVER

State: EXECUTING
Plan: follow_neptus
Man.: 1 (FollowReference)
Progress: N/A

N41.18468889°, W8.70608...
Transponders
  benthos2
  benthos4
Plans
  follow_neptus
  formation_template

System: lauv-noptilus-3 **Plan:** N/A

Figure 15 - Neptus (Execution)



State: EXECUTING
Plan: formation_lauv-xtreme-2
Man.: 3 (FollowTrajectory)

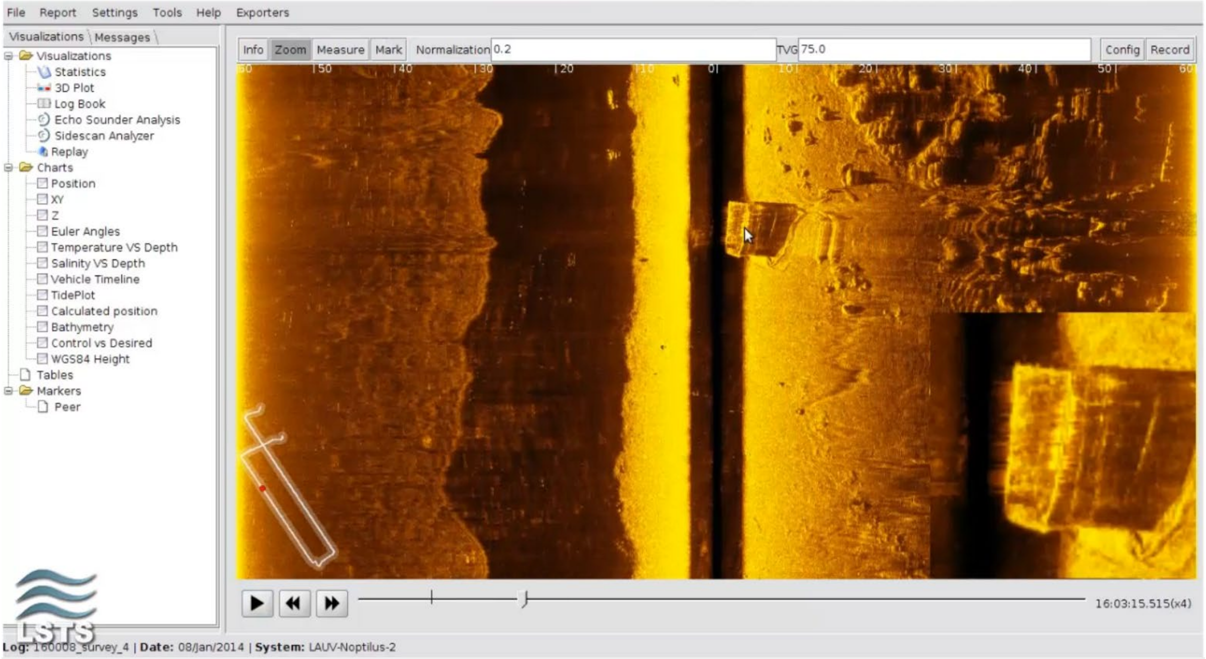
ystem: lauv-xtreme-2 **Plan:** formation_lauv-xtreme-2

Figure 16 - Neptus (Real-Time Data)

Review and Analysis. The review and analysis phase occurs on-site or after the mission is concluded. The collected data is processed and analysed to compile the mission results or evaluate individual plan execution to adjust and re-plan to achieve another desired outcome.

For this purpose, Neptus includes two specific tools, the Operator Console and the Mission and Review and Analysis tool.

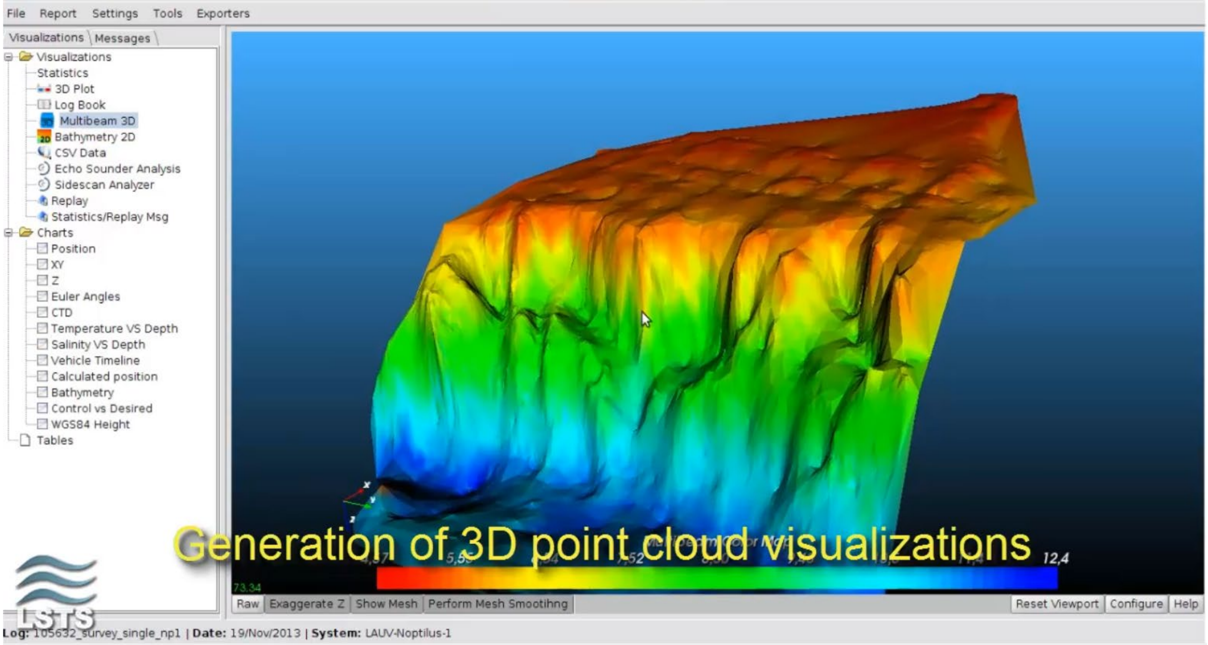
A plug-in infrastructure can extend the C2 software framework. The plug-ins can be visual widgets in the console, pop-ups, map layers, or even daemons running in the background. Some consoles are tailored for multi-vehicle supervision, while others allow manual control of teleoperated vehicles with the video feed and joystick input. The operator can easily adapt the consoles to specific mission needs or vehicle specifications.



Log: 160008_survey_4 | Date: 08/Jan/2014 | System: LAUV-Noptilus-2

Figure 17 - Netpus (Review and Analysis - SideScan).

Figure 17 illustrates that users can integrate different sensor payloads and the previously integrated ones are already available.



Log: 105632_survey_single_np1 | Date: 19/Nov/2013 | System: LAUV-Noptilus-1

Figure 18 - Netpus (Review and Analysis - Bathymetry)

Oceanographic Decision Support System (ODSS)

The ODSS[3] was developed as part of the CANON (Controlled, Agile, and Novel Observing Network) program by MBARI, based upon lessons learned from the previous AOSN program, with the goal to detect and track spatiotemporal coastal ocean features and to enhance the technology to enable observations of such spatiotemporal phenomenon.

The ODSS system was designed, built, tested, and fielded as a decision support system that provides a platform for **situational awareness, planning, observation, collaboration, archiving, and data analysis**. ODSS was described as an effort to transition existing services into a layered architecture to serve various users and machine-facing components.

Architecture. The ODSS aims to allow ocean scientists to collaboratively design their experiments, communicate with other participants, track asset locations, and command robotic vehicles at sea, by providing a single framework aimed to tackle each component of the system which was categorised as (1) situational awareness, (2) experiment planning, (3) collaboration, and (4) data analysis, enabled as the main features for their one-stop portal (ODSS client).

The ODSS client or web browser is connected to an ODSS Server instance handling services for data processing, mapping, storage, catalogue, and analysis, as well as asset tracking.

A major component of the ODSS is the Communication Backplane, allowing the integration of heterogeneous fleets of platforms and sensors by enabling an exchange of data through multiple communication protocols and external networks to the server. The ODSS Server can also be virtualized to multiple instances at different locations, synchronised through the Communication Backplane. An overview of the architecture is shown in Figure 19 [below].

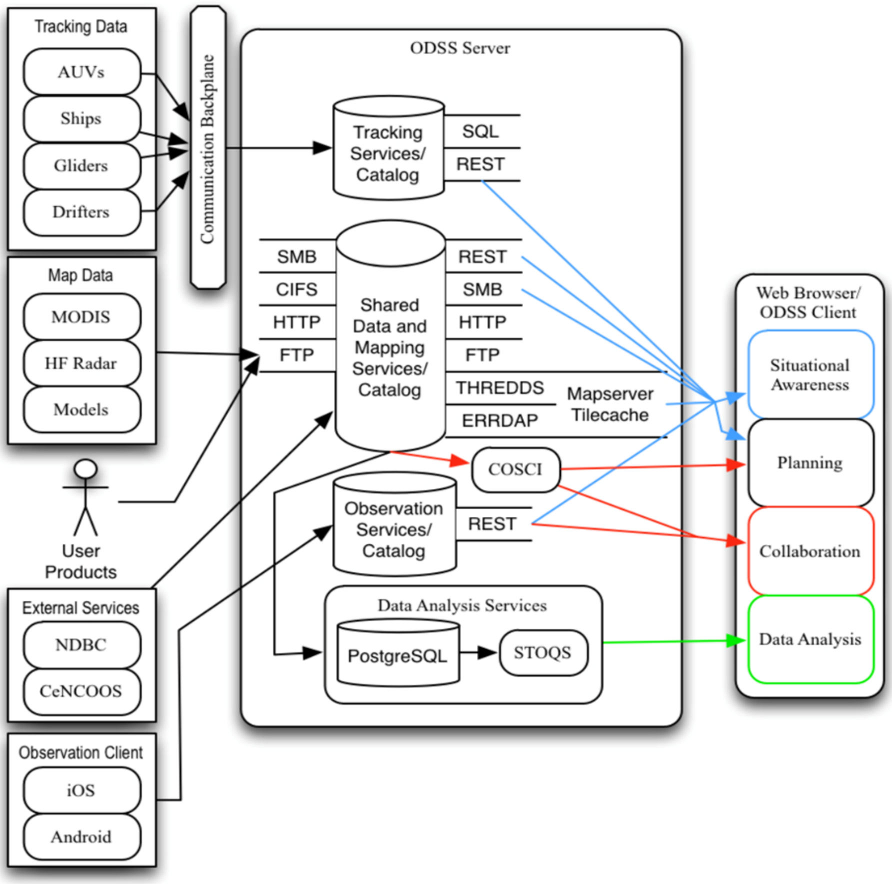


Figure 19 - High-level architecture of ODSS

Communication Backplane. The primary wireless link types in the system include:

- Maritime Very Small Aperture Terminal (VSAT) satellite terminal for shipboard communication (TCP-IP protocol);
- Line-of-sight radio (cellular or 900 MHz, TCP-IP protocol);
- Iridium satellite short burst data (SBD) messages (Iridium modem and email).

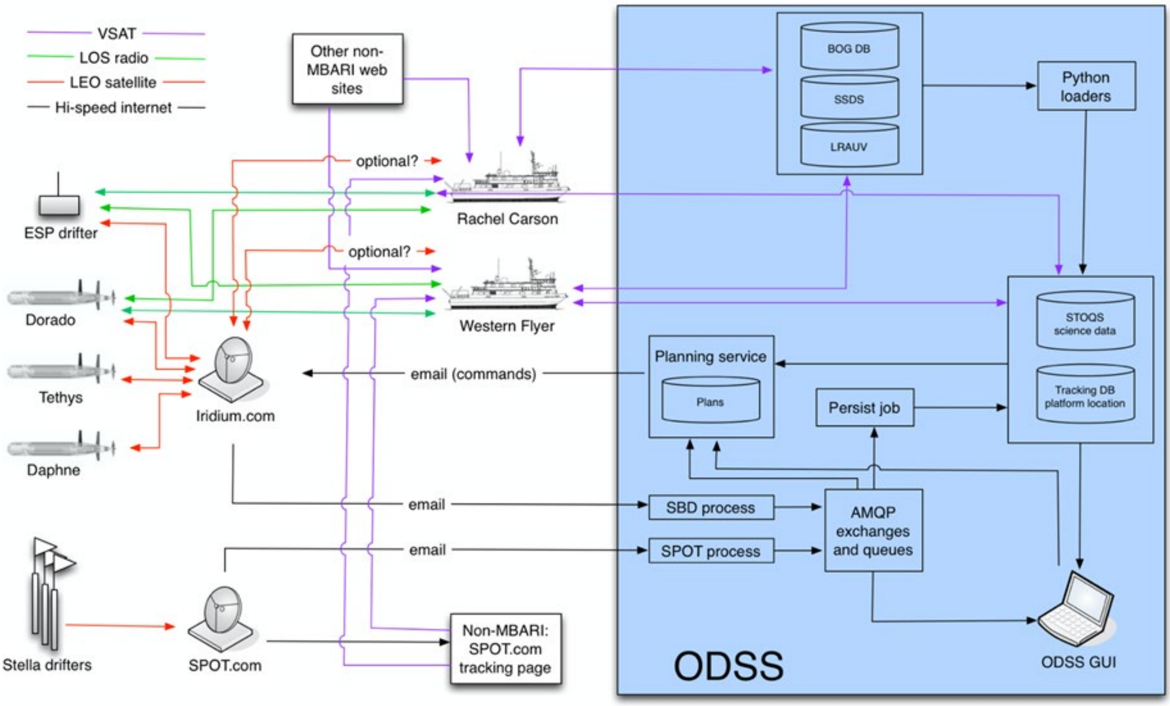


Figure 20 - ODSS Communication backplane

Adapters were developed to convert data transferred across the heterogeneous transport links to a common protocol using Google Protocol Buffers, and then these messages are published to an Advanced Message Queuing Protocol (AMQP) *RabbitMQ* server. The *RabbitMQ* server also allows data to be shared across multiple instances of the ODSS or other more lightweight tracking services and provides a simple way for platform managers to integrate their vehicles into the system. The Communication Backplane also uses the *rsync* protocol as a data transport mechanism over the TCP-IP link to synchronise files and directories between instances of the ODSS servers, or between shore-based and on-ship servers.

Future work and lessons learned:

1. Several important lessons have been learned based on extensive use of the ODSS during their work in the development, testing, and deployment of the system; Duplicate ODSS instances onboard field vessels are critical for field operations;
2. Providing synchronisation between multiple ODSS instances makes operations more efficient for both shore and ship-based personnel;
3. The *rsync* utility had some drawbacks that may drive an investigation of other synchronisation options,
4. Simple file storage and catalogue as the first point of entry for sharing data is a necessity for customer adoption;

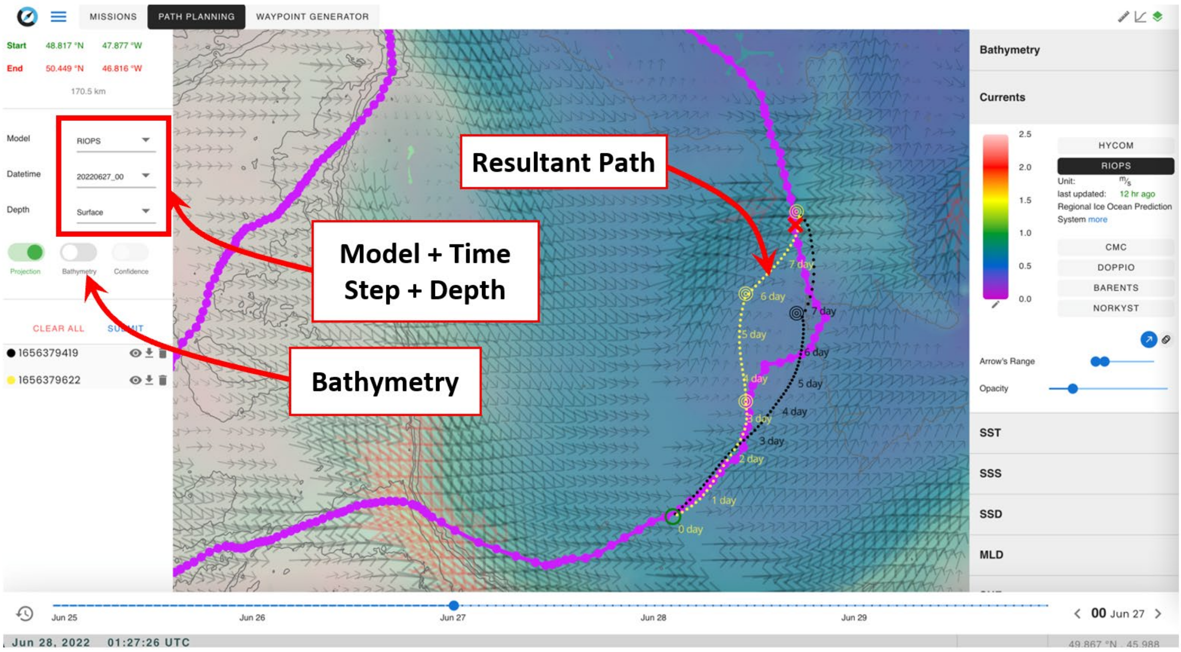
5. A service-based architecture with standard protocols and APIs is important for the integration of a diverse set of services and customers;
6. Gathering engineering requirements from diverse groups performing infrequent field experiments is extremely difficult and pushes to an agile development methodology.

Other tools

This section reviews some tools and systems that have been developed to aid the piloting of MAS or are C2 systems on their own merit but that have been considered slightly less relevant for the report.

OceanGNS

OceanGNS (Ocean Glider Navigation System) [4] offers a collection of software and cloud-based computing to make navigation suggestions for AUVs such as map layers for data from satellites, Argo floats, altimetry, and AIS. OceanGNS integrates current forecasts and historical data to enable glider route planning at varying scales.



Start 48.817 °N 47.877 °W
End 50.449 °N 46.816 °W
170.5 km

Model: RIOPS
Datetime: 20220627_00
Depth: Surface

● 1656379419
● 1656379622

Unit: m/s
last updated: 12 hr ago
Regional Ice Ocean Prediction System more

00 Jun 27

Jun 28, 2022 01:27:26 UTC

49.867 °N 45.988

Figure 21 - OceanGNS main ui showing current vectors, a planned route and some relevant UI elements.

The route planner in OceanGNS finds the optimal route for a glider by minimising low current velocity constraints by applying a Dijkstra algorithm with additional considerations such as reducing the complexity of the resultant path and adding bathymetric information to a cost function when avoiding shallow water.

Beluga

BELUGA [5], developed by GEOMAR Helmholtz Centre for Ocean Research Kiel, is an advanced system designed to exhibit and track platforms and their measurement data in real-time while operating at sea. The system receives data from platforms and presents it with their corresponding positions through an intuitive user interface, the BELUGA Navigator. The displayed data can be viewed directly on board and is also shared online in near real-time through an interface. Besides data visualization, BELUGA allows seamless communication with platforms both above and below the water level.

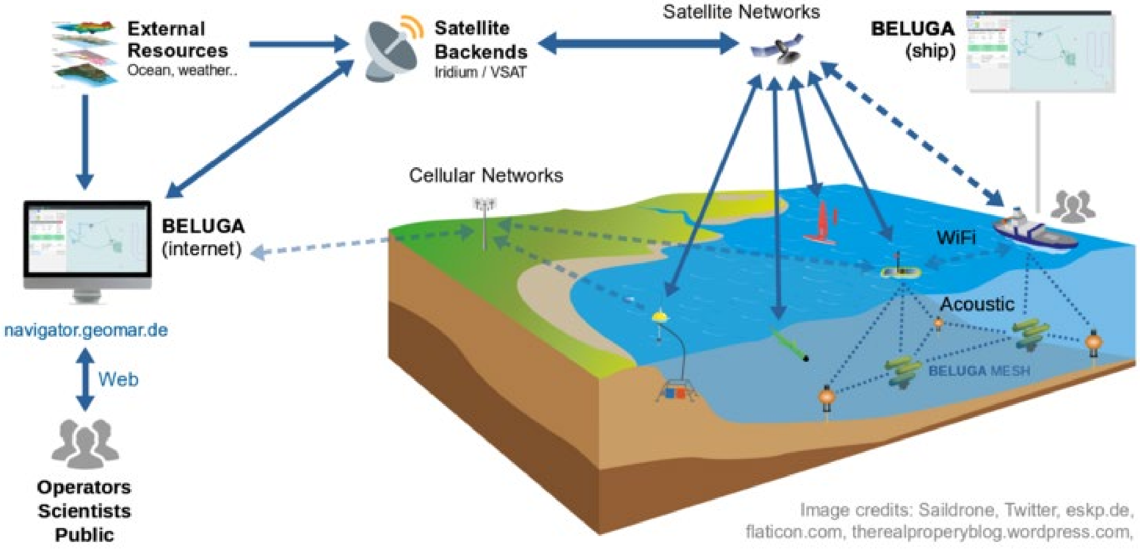
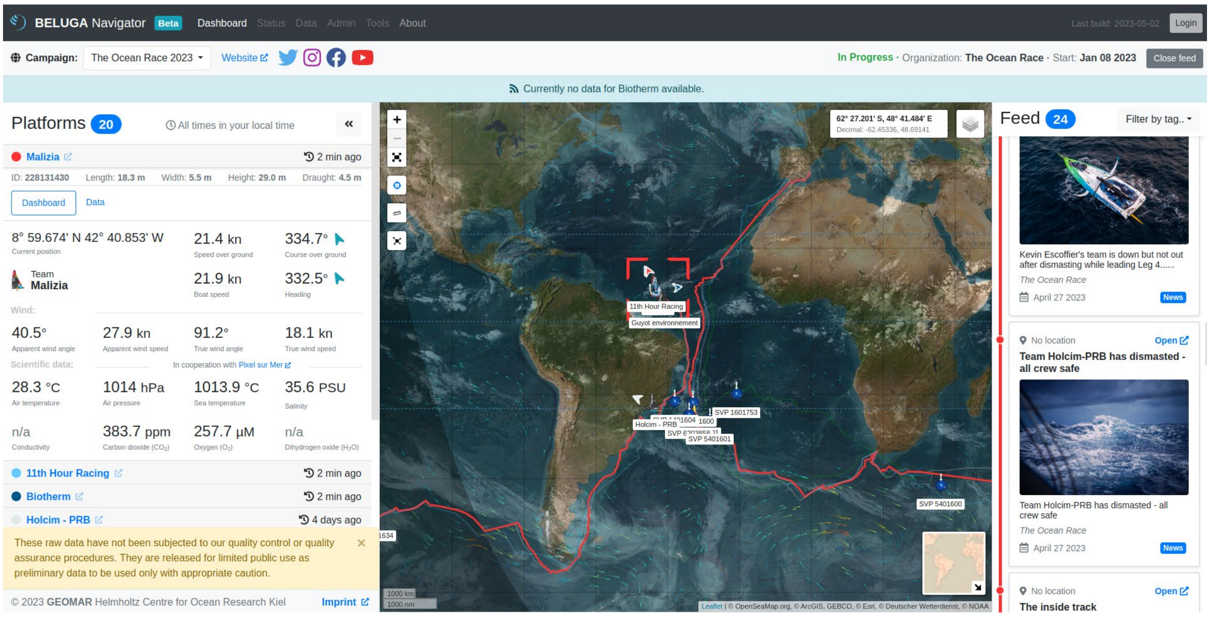


Figure 22 - Data flow of the BELUGA system

Features of BELUGA:

- Monitoring and Control of Platforms
  - Communication with platforms above and underwater
  - Automatic selection of the communication channel
  - Display of platform positions on the map (situational awareness)
  - Customised dashboards per platform type
  - Positioning
- Data Visualisation
  - Real-time overview of received data on board
  - Display of data in charts
  - Integration of external data into the map
  - Daten-Export
- Outreach
  - Display of campaigns
  - Medien-Feed



Last build: 2023-05-02

Campaign: The Ocean Race 2023

In Progress · Organization: **The Ocean Race** · Start: **Jan 08 2023**

Currently no data for Biotherm available.

Malizia – 2 min ago

ID: **228131430** Length: **18.3 m** Width: **5.5 m** Height: **29.0 m** Draught: **4.5 m**

8° 59.674' N 42° 40.853' W Current position	21.4 kn Speed over ground	334.7° Course over ground
Team **Malizia**	21.9 kn Boat speed	332.5° Heading

Wind:

40.5° Apparent wind angle	27.9 kn Apparent wind speed	91.2° True wind angle	18.1 kn True wind speed

Scientific data: In cooperation with Pixel sur Mer

28.3 °C Air temperature	1014 hPa Air pressure	1013.9 °C Sea temperature	35.6 PSU Salinity
n/a Conductivity	383.7 ppm Carbon dioxide (CO_2)	257.7 µM Oxygen (O_2)	n/a Dihydrogen oxide (H_2O)

11th Hour Racing – 2 min ago

Biotherm – 2 min ago

Holcim - PRB – 4 days ago

These raw data have not been subjected to our quality control or quality assurance procedures. They are released for limited public use as preliminary data to be used only with appropriate caution.

© 2023 **GEOMAR** Helmholtz Centre for Ocean Research Kiel **Imprint**

62° 27.201' S, 48° 41.484' E
Decimal: -62.45336, 48.69141

Kevin Escoffier's team is down but not out after dismasting while leading Leg 4......
The Ocean Race
April 27 2023 News

No location Open
Team Holcim-PRB has dismasted - all crew safe
Team Holcim-PRB has dismasted - all crew safe
The Ocean Race
April 27 2023 News

No location Open
The inside track

Figure 23 - BELUGA Navigator main ui

Summary of features

The following table summarises the characteristics and features supported by these different C2 systems.

	SFMC / Dockeserver	**Basestation / SG Piloting Tools**	**Glimpse**	**EGO GFCP**	**NOC C2**	**LSTS Neptus**	**ODSS**
Compatible Vehicles	Slocum	Seaglider	Seaxplorer	Seaglider, Slocum and Sprays (limited support)	Seaglider, Slocum, NOC Autosubs	LSTS vehicles and integration with multiple MAS	Project- depended (AUVs, ASVs, gliders, drifters)
Manufacturer Tool	Yes	Yes	Yes	No	No	No	No
Web based	SFMC	No	Yes	Yes	Yes	No	Yes
Desktop client	Deprecated	Piloting tools	Deprecated	No	Yes (C2iAB)	Yes	Yes
Open Source	No	No	No	No	No (planned)	Yes	Some parts
Multi-vehicle Piloting	Yes Can access multiple vehicles	Yes	Yes Can access multiple vehicles	Yes Can access multiple vehicles	Yes Can access multiple vehicles	Yes Unified multiple vehicles	Yes
Built-in Console / Terminal	Yes	?	?	Yes	Yes	No	No
Primary user group	Pilots, Scientists	Pilots, Scientists	Pilots, Scientists	Pilots, Scientists	Pilots	Pilots	Pilots, Scientists
Features							
Access control	SFMC/DDockserver Linux	Basestation on linux	✕	✕	✕	✕	✕
Map	SFMC	No	✕	✕	✕	✕	✕
Human pilot entered logs			?	Kindoff	✕	✕	✕
Vehicle state	✕	✕	✕	Kindoff	✕	✕	✕
Modify vehicle's configuration independently	✕	✕	✕	✕	✕	✕	No
Schedule sending new orders to the vehicles	No	No	?	No	✕	✕	No

Configure piloting rotation/scheduling	No	No	?	✕	No	✕	No
File storage (to & from vehicles)	✕	✕	?	✕	✕	✕	✕
Download files	✕	✕	?	✕	✕	✕	✕
Science plots (temperature vs salinity)	✕	Piloting tools	✕	✕	✕	✕	✕
Science plots (oxygen & par sensor)	✕	Piloting tools	✕	✕	✕	✕	✕
Science plots (CTD)	✕	Piloting tools	✕	✕	✕	✕	✕
Dive plots	✕	Piloting tools	✕	✕	✕	✕	✕
Bespoke plots	✕	No	?	No	No	?	✕
Battery endurance calculator	No	No	?	✕	✕	✕	No
Leak detection plot	✕	✕	?	✕	✕	✕	No
Notification when glider calls-in	✕	✕	✕	✕	✕	?	No
API	✕	No	?	No	✕	Used for Ripples the front-end of Neptus	✕

Table 2 - Summary of Features (Piloting tools)

Appendix 2 - Autonomy experiments

This section describes some experiments with enhanced autonomy. Most of them have been bespoke. We will identify their objectives, extract learning to make those types of activities sustainable in the future GROOM RI and draw parallelisms with the GROOM use cases.

The Autonomous Ocean Sampling Network

The Autonomous Ocean Sampling Network (AOSN) [6] pioneering project in the field of autonomy in oceanography aimed at designing and building an adaptive coupled observation/modelling system. The project's approach to improving its ability to observe and predict the ocean was by assimilating advanced ocean models with satellite and in situ data obtained from a variety of sensor arrays and marine autonomous systems (MAS) and then used to adaptively deploy and manoeuvre mobile assets to optimise detection and measurement of particular fields of interest, in real-time (hours). The project also required them to design and develop a mechanism to coordinate deployments of assets, which includes both crewed and uncrewed MAS, as well as the incorporation of models and data from multiple institutions.

There were two field programs in Monterey Bay run to demonstrate their system between mid-July and mid-September of 2003 (MB2003) and 2006 (MB2006). MB2003 consisted of collaboration work of over a dozen different institutions (consisting of various universities and research institutions), and the following assets/platforms:

- 12 Slocum gliders
- 5 Spray gliders
- 4 autonomous underwater vehicles (AUVs) of varying size, depth, and endurance
- 4 research vessels (2 for data collection and 2 for launch and recovery)
- 4 satellites
- 6 other platforms and instruments including sensor arrays, moorings, drifters, profilers, and aircraft.

MB2006 also involved multiple institutions, thirteen research vessels, over three dozen AUVs, and many other fixed and drifting oceanographic instruments.

The operational system design was divided into three main categories, namely:

Data Assimilation

Data collection by adaptive platforms and sensors were relayed to a shore, usually by Iridium, where they are assimilated into numerical models, together with remote sensing or satellite data, to create four-dimensional fields of nowcasts and forecast predictions.
The AOSN data management system was designed to have minimal requirements for both the scientists generating data (i.e., to continue their excellent data generation and data management,

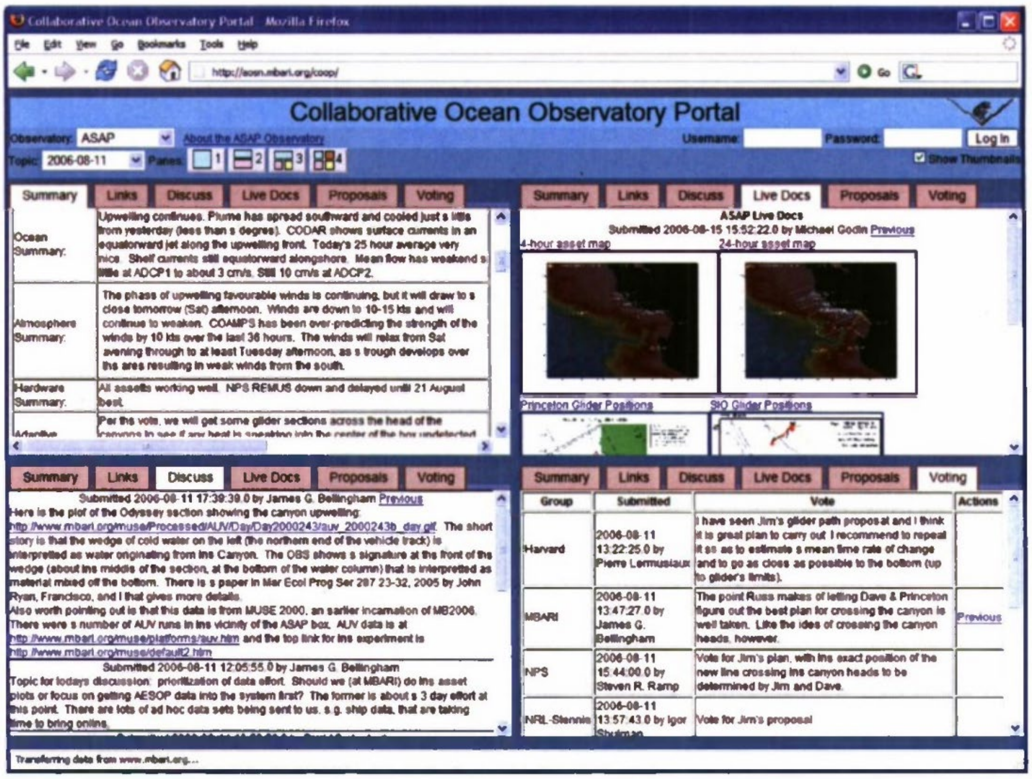
ensuring that their data are internally consistent) and users (i.e., a computer with a modem web browser and internet access).

Adaptive Sampling

A two-pronged strategy was used for planning for the field research. The first is to develop a method to intelligently select observing locations, using historical data, informed by capturing the leading spatial modes (or a small number of selected locations), and then, to estimate and reconstruct the full field. Selection is made by simple sorting. The second is to design sampling strategies for estimating ocean flux, or real-time dynamics, with ocean model data and using moorings or AUVs.
Data was captured throughout the field experiment to data servers at MBARI, Harvard, and JPL and were assimilated in real-time into the Harvard Ocean Prediction System (HOPS) and Regional Ocean Modelling System (ROMS) models. The models provided forecast products for the development of adaptive sampling plans, which were then used to reprogram gliders and redeploy other assets. Data from these assets were communicated to shore, where they were placed in a central repository that could be accessed by modelling groups and other collaborators. Models provide a powerful tool for the integration of information from a variety of observational sources into a representation of the best estimate of the ocean state.

Collaborative Design

For the MB2006 Experiment, the Shore Side Data System (SSDS) data catalogue and Metadata Oriented Query Assistant (MOQuA) prototype for data exploration and management were developed. Principal Investigators (PI) would interact with the data system and a wide range of derived products (processed data and analysis plots) via a web-based Cooperative Ocean Observatory Portal (COOP) as a central hub for collaboration work between project partners. COOP is used for daily discussions, planning for data collection, as well as reviewing daily progress, analyzing results, and proposing actions.



Ocean Summary:	Upwelling continues. Plume has spread southward and cooled just a little from yesterday (less than a degree). CODAR shows surface currents in an equatorward jet along the upwelling front. Today's 25 hour average very nice. Shelf currents still equatorward alongshore. Mean flow has weakend a little at ADCP1 to about 3 cm/s. Still 10 cm/s at ADCP2.
Atmosphere Summary:	The phase of upwelling favourable winds is continuing, but it will draw to a close tomorrow (Sat) afternoon. Winds are down to 10-15 kts and will continue to weaken. COAMPS has been over-predicting the strength of the winds by 10 kts over the last 36 hours. The winds will relax from Sat evening through to at least Tuesday afternoon, as a trough develops over the area resulting in weak winds from the south.
Hardware Summary:	All assets working well. NPS REMUS down and delayed until 21 August best.
Adaptive	Per the vote, we will get some glider sections across the head of the

Submitted 2006-08-15 15:52:22.0 by Michael Godin Previous

Submitted 2006-08-11 17:39:39.0 by James G. Bellingham Previous

Here is the plot of the Odyssey section showing the canyon upwelling: http://www.mbari.org/muse/Processed/AUV/Day/Day2000243/auv_2000243b_day.gif. The short story is that the wedge of cold water on the left (the northern end of the vehicle track) is interpreted as water originating from the Canyon. The OBS shows a signature at the front of the wedge (about the middle of the section, at the bottom of the water column) that is interpreted as material mixed off the bottom. There is a paper in Mar Ecol Prog Ser 287 23-32, 2005 by John Ryan, Francisco, and I that gives more details.

Also worth pointing out is that this data is from MUSE 2000, an earlier incarnation of MB2006. There were a number of AUV runs in the vicinity of the ASAP box. AUV data is at http://www.mbari.org/muse/platforms/auv.htm and the top link for the experiment is http://www.mbari.org/muse/default2.htm

Submitted 2006-08-11 12:05:55.0 by James G. Bellingham

Topic for todays discussion: prioritization of data effort. Should we (at MBARI) do the asset plots or focus on getting AESOP data into the system first? The former is about a 3 day effort at this point. There are lots of ad hoc data sets being sent to us, e.g. ship data, that are taking time to bring online.

Group	Submitted	Vote	Actions
Harvard	2006-08-11 13:22:25.0 by Pierre Lermusiaux	I have seen Jim's glider path proposal and I think it is great plan to carry out. I recommend to repeat it so as to estimate a mean time rate of change and to go as close as possible to the bottom (up to glider's limits).	
MBARI	2006-08-11 13:47:27.0 by James G. Bellingham	The point Russ makes of letting Dave & Princeton figure out the best plan for crossing the canyon is well taken. Like the idea of crossing the canyon heads, however.	Previous
NPS	2006-08-11 15:44:00.0 by Steven R. Ramp	Vote for Jim's plan, with the exact position of the new line crossing the canyon heads to be determined by Jim and Dave.	
NRL-Stennis	2006-08-11 13:57:43.0 by Igor Shulman	Vote for Jim's proposal	

Transferring data from www.mbari.org...

Figure 24 - Collaborative Ocean Observatory Portal (COOP)

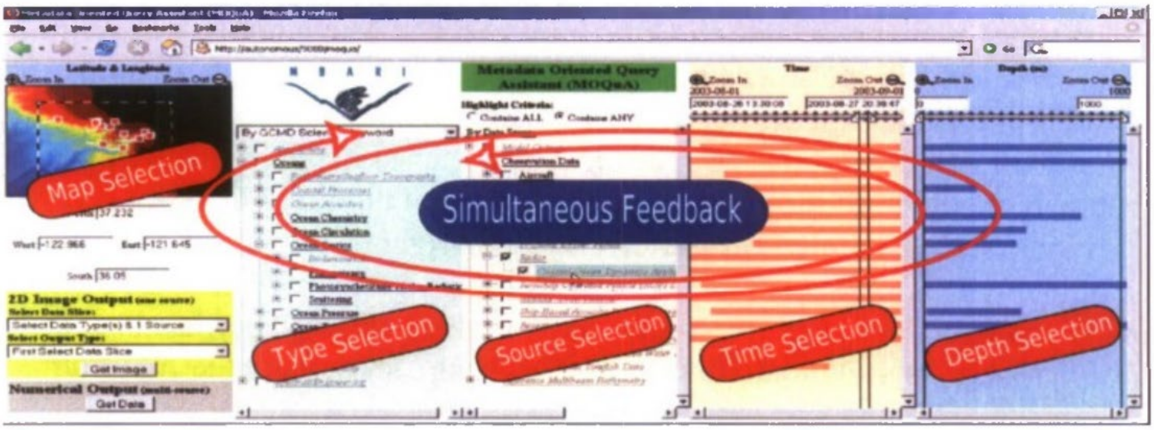


Figure 25 - Metadata Oriented Query Assistant (MOQuA)

Studying Eddies in the Mediterranean Sea

As part of the EGO network's community activities, three campaigns were carried out between 2007 and 2009, involving 6 to 9 gliders of different types (Slocum, Seaglider and Spray) and belonging to different institutes, namely CNRS, NOC, GEOMAR and OGS. In addition to scientific objectives concerning the study of the mesoscale activity in the north-western Mediterranean region where convection occurs in winter (EGO 2007 and EGO 2008) and the study of the "Cyprus eddy" (EYE 2009), these exercises used the GFCP, including some automation functions for navigation and waypoint assignment described above (section 4.2.1).

They were the first demonstration in Europe by those who are now partners in the GROOM II project (or are associated with its activities in the case of OGS) of the ability to conduct this type of "glider fleet mission". It was largely during these campaigns that the need to build a distributed infrastructure for the burgeoning field of "glider science" became apparent. The COST Action EGO, then the GROOM project supported by FP7, followed in their wake.

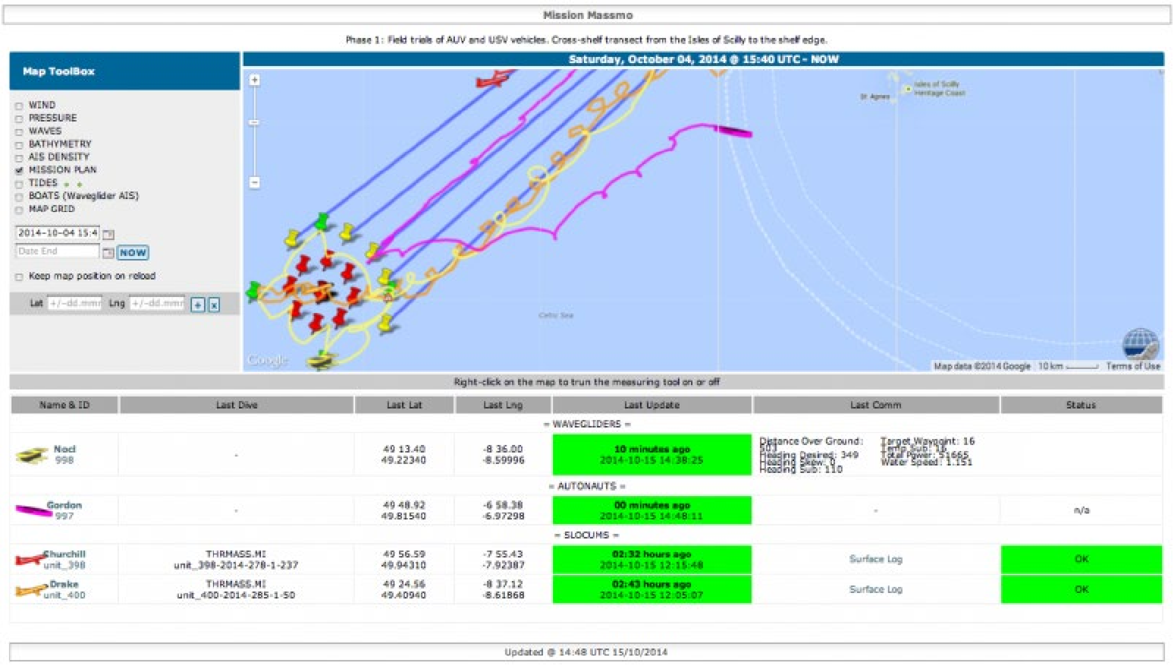
MASSMO

The Marine Autonomous Systems in Support of Marine Observations (MASSMO) [7] project was one of the pioneering multi-partner series of trials and demonstrator missions that aim to explore the UK seas using a fleet of innovative marine robots. The ambitious multi-phased project was touted to have carried out the largest single deployment of marine autonomous systems (MAS) ever in the UK during its time, testing newly developed capabilities and autonomous platform fleets consisting of a variety of gliders and uncrewed surface vehicles (USV).

The project successfully completed five missions over the course of four years from 2014 to 2018, namely:

1. MASSMO 1
    a. 1/10/2014 - 31/10/2014 in the Isles of Scilly
    b. Five USVs (1 C-Enduro, 1 Autonaut, 3 WaveGliders)
2. MASSMO 2
    a. 19/5/2015 - 5/6/2015 in the Celtic Deep area of the Celtic Sea in partnership with WWF
    b. One Slocum glider and one C-Enduro USV
3. MASSMO 3
    a. 15/9/2016 - 2/10/2016 in Northwest Scotland
    b. Seven gliders (6 Slocum, 1 SeaGlider) and three WaveGliders
4. MASSMO 4
    a. 19/5/2017 - 7/6/2017 in the Faroe-Shetland Channel
    b. Two USVs (1 Autonaut, 1 C-Enduro), one WaveGlider, and 5 gliders (1 SeaGlider, 4 Slocums)
5. MASSMO 5
    a. 17/10/2018 - 25/10/2018
    b. Two gliders (Slocum) and two micro-AUVs (ecoSUB)
    c. 3D visualisation of glider data integrated with satellite data and model outputs

The yearly missions were executed with laborious planning efforts between multiple partners including research institutions, and governmental and commercial organisations. Each year, ambitious projects consisting of varied deployments' objectives and locations were undertaken with a fleet of heterogeneous MAS platforms. MASSMO have shown that multiple MAS of different types can be deployed concurrently to complement one another — exploiting the different capabilities of each vehicle type to meet a range of science objectives and stretching their capabilities to collect observation data over a longer duration at sea.



Mission Massmo

Phase 1: Field trials of AUV and USV vehicles. Cross-shelf transect from the Isles of Scilly to the shelf edge.

Saturday, October 04, 2014 @ 15:40 UTC - NOW

Map ToolBox

☐ WIND
☐ PRESSURE
☐ WAVES
☐ BATHYMETRY
☐ AIS DENSITY
☑ MISSION PLAN
☐ TIDES
☐ BOATS (Waveglider AIS)
☐ MAP GRID

2014-10-04 15:4
Date End
NOW

☐ Keep map position on reload

Lat +/-dd.mmm Lng +/-dd.mmm

Right-click on the map to trun the measuring tool on or off

Name & ID	Last Dive	Last Lat	Last Lng	Last Update	Last Comm	Status
= WAVEGLIDERS =						
Nod 998	-	49 13.40 49.22340	-8 36.00 -8.59996	10 minutes ago 2014-10-15 14:38:25	Distance Over Ground: 503 Heading Desired: 349 Heading Skew: 0 Heading Sub: 110 Target Waypoint: 16 Temp Sub: 16 Total Power: 51665 Water Speed: 1.151	
= AUTONAUTS =						
Gordon 997	-	49 48.92 49.81540	-6 58.38 -6.97298	00 minutes ago 2014-10-15 14:48:11	-	n/a
= SLOCUMS =						
Churchill unit_398	THRMASS.MI unit_398-2014-278-1-237	49 56.59 49.94310	-7 55.43 -7.92387	02:32 hours ago 2014-10-15 12:15:48	Surface Log	OK
Drake unit_400	THRMASS.MI unit_400-2014-285-1-50	49 24.56 49.40940	-8 37.12 -8.61868	02:43 hours ago 2014-10-15 12:05:07	Surface Log	OK

Updated @ 14:48 UTC 15/10/2014

Figure 26 - NOC MARS Portal Dashboard during MASSMO 1 showing the planned tracks and the fleet state.

Within MASSMO, the vehicles themselves have their own individual schedules and sampling paths to follow and do not interact with each other in meaningful ways. However, each mission yielded significant quantities of environmental, acoustic, and bathymetry data. Data collected are submitted in the form of delayed-mode data to the Ocean Glider Programme, a global data assembly centre, and the submission of NRT data to the UK Met Office. During MASSMO 5, the EGO files produced by the C2 data processing system were visualised by project partners including Plymouth Marine Laboratory (PML) and the Scottish Association for Marine Science (SAMS).

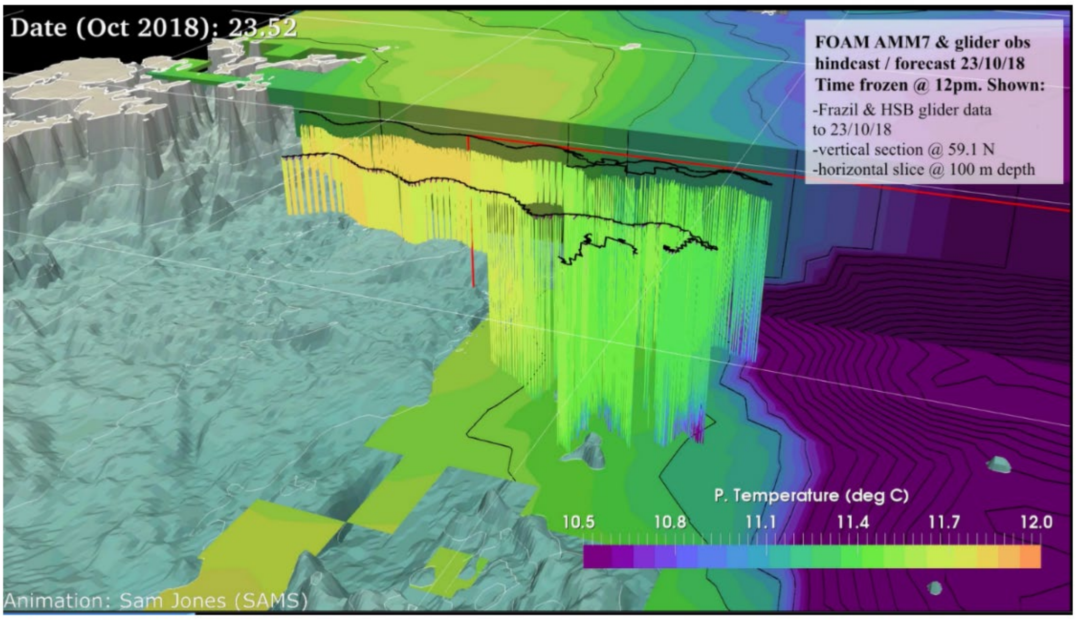


Figure 27 - 3D AMM7 Visualization Produced by SAMS during MASSMO 3 to be presented during the experiment daily briefings.

The figure above shows a 3D visualisation of the AMM7 model vs glider data during the MASSMO5b mission. The modelled temperature consists of a vertical slice at 59.1ºN and a horizontal plane at a depth of 100 m to reveal data. Glider surface tracks are shown by black lines, and glider-measured temperature data are vertical coloured lines. The colour scale for the model and glider are identical. Note the colour scale has been optimised for showing the temperature range of the glider data. The red box denotes the planned glider transect along 59ºN. Bathymetry is GEBCO gridded product.

Hardware failures, expected or otherwise, become a major issue at this scale, adding more to the planning requirements and costs in ensuring the success of each deployment. Feedback and lessons learned during these trials were subsequently fed into requirements for future development.

REPMUS

REPMUS stands for Robotic Experimentation and Prototyping Augmented by Maritime Unmanned Systems and is the largest annual robotics exercise in Portugal that brings together international navies, and academic and industrial research institutions in an effort to test and put into practice technologies and concepts that allow for more efficient operations.

The REP exercise had its first edition in 2010, in a collaboration between the Faculty of Engineering of the University of Porto, through the LSTS, and the Portuguese Navy. In 2015, the NATO Science and Technology Organization Center for Maritime Research and Experimentation (CMRE) became another co-organizer, and they were joined by the NATO Maritime Unmanned Systems Initiative (NATO MUSI) in 2019. Currently, the REPMUS exercise is co-organized by the four institutions.

Exercises REPMUS22 and DYMS22 (Dynamic Messenger 22) present opportunities to test the interoperability of new maritime unmanned systems, ensuring that Allies can work together to counter future security challenges. REPMUS is more oriented on testing and training and DYMS focuses on practical operations training with new marine technologies and readiness.

Dynamic Messenger is the first full NATO operational experimentation exercise that specifically focuses on integrating unmanned systems into the maritime domain, and more specifically NATO Task Groups at sea, with more than 18 ships, 48 unmanned assets, and 1500 personnel from 16 NATO nations participating. Through a CATL message protocol, unmanned vehicles report their status between the different institutions/nations, synchronised missions between different nodes, and have a global picture improving the situational awareness of all the operators.

UPORTO On the Falkor

The approach to open ocean exploration combining multiple assets and sensors in a cohesive networked environment was tested during the Exploring Fronts with Multiple Robots cruise to explore a frontal zone in the open waters of the Pacific[8]. Along with a range of sensors aboard the research vessel R/V Falkor - Schmidt Ocean Institute - augmented by autonomous surface, aerial and underwater vehicles allowed to expand the footprint of an oceanographic research vessel.

Different assets were connected to the ship in varied ways. However, all the data was aggregated in a cloud to be accessed from the ship and any other location connected to the Internet, such as the Ocean Space Center, located in Portugal, ten time zones away. From the Falkor, scientists received real-time measurements from ships' sensors and robotic assets above and below the ocean surface.

The figure below shows the overall system architecture and network in the context of exploring the Northern Pacific Subtropical Front.

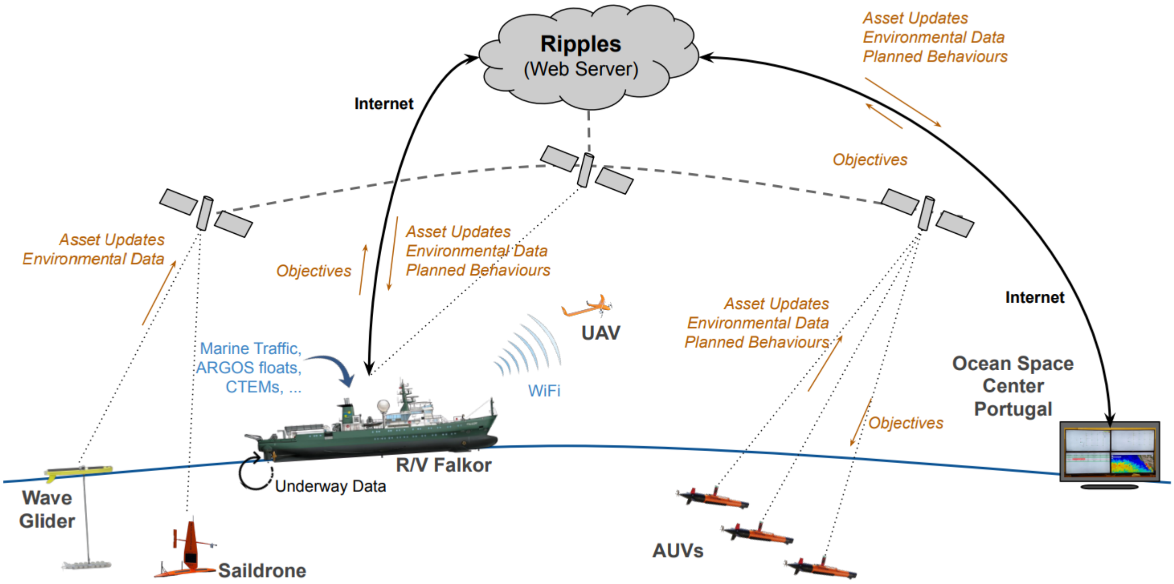


Figure 28 - System Architecture and Network of the LSTS-Toolchain as deployed for the Falkor operation.

To address all the crewed and uncrewed systems and the users connecting from different locations around the world, we rely on different components of the LSTS-Toolchain.

Appendix 3 - CATL an autonomy standardisation protocol

In order to ensure interoperability of an autonomous system, despite the environmental domain (e.g. land, air, marine, space), where teams of assets from various allies may be called to complete a common mission, it is necessary that all different nodes "speak the same language".

To accomplish a similar type of operation, the NATO SCI-288/343 Research Task Group developed a conceptual message protocol, allowing tasks to be shared among assets or groups of assets using different autonomy mission software. This was called CATL (Collaborative Autonomy Task Layer).

The driving force for this effort was military tasks, which consisted of MCM (Mine Counter Measurements) and ASW (Anti-Submarine Warfare). While these tasks don't fall into the GROOM II operations, the idea and concept can be added or adapted.

Model specification

The CATL formally defines an abstract, extensible data model to be used for messages and for tasks and also advises and develops security-related aspects for federated military operations. In order to fit the context of civilian/environmental research the model described below may be more suitable.

Asset. This asset structure contains the information and description of an uncrewed vehicle.

The implementation is glider oriented but it can be expanded for all different types of vehicles independent of the environmental domains (e.g. land, air, surface).

```
{
 "name" : "..." ,
 "imcid" : -1 ,
 "lastState" : {
  "latitude" : 37.85011 ,
  "longitude" : -8.79306 ,
  "heading" : 0.0 ,
  "fuel" : 0.0 ,
  "timestamp" : 165393914
 }
 "domain" : [],
 "type" : "..." ,
 "plan" : {
  "id" : "..." ,
  "waypoints" : [] ,
  "description" : "..." ,
  "type" : "...",
  "survey" : true
```

```
  }
}
```

Asset state. The state allows us to describe the position reported from the asset and fuel available.

```
{
  "latitude" : 37.85011 ,
  "longitude" : -8.79306 ,
  "heading" : 0.0 ,
  "fuel" : 0.0 ,
  "timestamp" : 165393914
}
```

Plan. The plan message allows us to describe plans that can be executed by unmanned vehicles.

```
{
  "id" : "..." ,
  "waypoints" : [],
  "description" : "..." ,
  "type" : "...",
  "survey" : "..."
}
```

Waypoints. Help us to describe each point of a plan to execute.

```
{
  "latitude" : 37.85011 ,
  "longitude" : -8.79306 ,
  "timestamp" : 165393914 ,
  "duration" : 0 ,
  "depth" : 0
}
```

System Capabilities. Describe what are the system's capabilities.

```
{
  “systemName”: “…”,
  “manufacturer”: “…”
  "capabilities" : [“…”, ”…”, ”…”]
}
```

AIS Ship. Describe and store ships information (from AIS hub).

```
{
  “mmsi”: 11,
  “type”: 2,
  “name”: “…”,
  “heading”: …
  "latitude" : 37.85011 ,
  "longitude" : -8.79306 ,
  “sog”: …,
  “bow”: …,
  “stern”: …,
  “port”: …,
  “starboard”: …,
  “draught”: …,
  “destination”: …,
  “eta”: …,
  “isFriendly”: false
}
```